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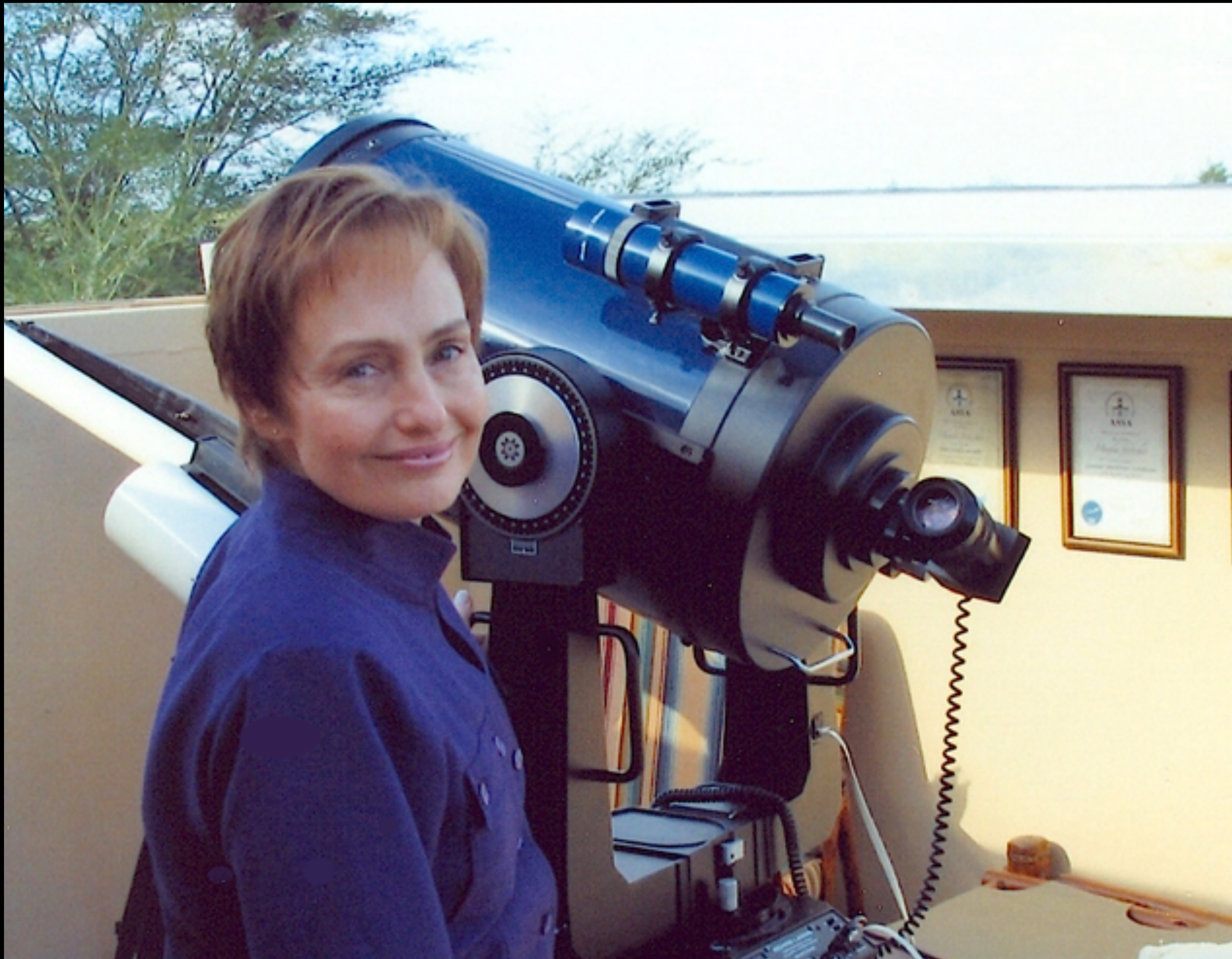


A visit to the Pulkovo Observatory

Magda Streicher

Never did I ever think that that a visit to Pulkovo Observatory would cross my path. But it did. In my thoughts reside visions of the great astronomers and telescopes of long ago. Those observers had walked through these front black iron gates, the road ahead framed with rich forest plants and trees, just as they welcomed me now. Ahead lay a building once used as a hotel for visiting astronomers from all over the world. Its best days were long long ago. The famed hotel of long ago has been reduced to a silent memory.

Pulkovo Observatory c.1860.

Before the visit I had gone to great lengths to secure an appointment with one of the astronomers who could show me the observatory. My heart sank when I arrived. There was no one in view, although the sign clearly indicated that this was the Pulkovo Observatory.

I kept following the road, hopeful and believing. Suddenly the stately building with the dome on the top showed the way. In summer, during the warmer weather, maintaining buildings is the norm and Pulkovo Observatory was no exception.

Because it is so far north, summer is the best time for astronomers to take their annual leave. Most of the individual observatory building were closed and could not be entered. My heart sank a second time. Still, I had faith that I would be provided with a guide. And sure enough, there he was. At the entrance to the main building with its large wooden doors I encountered a friendly young man who offered to show me the museum. He turned out to be an astronomer and lecturer working at the observatory.

It felt like walking back into history. The interior walls were adorned with large painted portraits of the astronomers who had opened up the universe in so many different ways. Old newspapers and scripts were housed in wooden boxes. Valuable refractors dating back to 1703 were showcased in glass cases. I was amazed to see the old observing chair, the sextants behind glass, and a sputnik that had circled the earth once before being parachuted back to earth. Seeing all this history in one room gave me a humble feeling.

My host was Maxim Khovritchev, who was there to study double stars. He offered to show me the great old Pulkovo refractor. It was still housed in an old wooden dome about 200 metres from the main building. The dome and refractor are still in perfect working order. The telescope still has the original box used to take glass plate pictures, though today it is equipped with a CCD camera.

Magda was escorted around the Pulkovo grounds by Maxim Khovritchev, a double-star astronomer at the Observatory, and an informative and congenial host.

One highlight for me was a stately hand-painted picture of the astronomer Friedrich Georg Wilhelm Struve (1793 – 1825). Today his name is often shortened to the nickname Vasily. In 1815 he married Emilie Wall (1796 – 1834) in Altona. She bore 12 children, only eight of whom survived early childhood. After his first wife died, Vasily remarried, to Johanna Henriette Francisca Bartels (1807 – 1867), a daughter of the mathematician Martin Bartels. She bore him six more children.

Friedrich Georg Wilhelm von Struve (1793–1864) developed an early, and lifelong, passion for double stars. His first work on these stars was published in 1813-1814. Newly graduated from the University of Dorpat (now Tartu, Estonia's second city) in what was then part of the Russian Empire, the young Struve filled his clear nights observing and logging stars (at a rate of up to 400 per hour!), and his cloudy nights compiling a comprehensive catalog of possible double stars observable from the northern hemisphere down to declination 15° S. In 1826 he discovered the duplicity of α Comae Berenices. It says something about the quality of Tartu skies in those times that an object like M16 the Eagle Nebula was visible from the 58° N latitude of the observatory. Pity about Antares, though, it would be only 7° above the horizon.

Alas for me, Maxim had a prior appointment and soon had to leave! My heart sank once again. By then the receptionist had returned to her desk. She explained to me that she would try to find someone else to act as my guide. Unfortunately, she explained all this in Russian. I understood not a word.

After a while the door opened and in walked a lady who announced that she would show me the observatory grounds, which houses quite a few domes. I could not pronounce her name and now cannot remember it, but the memory of her tour is vivid in my mind. Her English was terribly poor and she knew it. She was my only option, so off we went to the upper roof of the main building housing the large observatory dome where Struve had worked and achieved such great success. The wood and steel in the old Observatory seemed made out of Russian perfection. Relying mainly on hand gestures and facial expressions, she did a fascinating job of touring the observatory with me.

Struve's first observatory was in the town of Tartu, the second largest town in Estonia. Struve became the director of the Dorpat Observatory there in 1818 and had access to its 9-inch Fraunhofer refractor. From 1824 to 1839 the Dorpat Fraunhofer was the largest telescope in the world, and the first telescope to be clock-driven.

Today the grand old refractor enjoys a somnolent, genteel retirement amid a museum room filled with old Pulkovo telescopes. The Observatory has produced an excellent English-language *History of the Old Observatory.*

The wooden steps leading to the doorway of his observatory were once Struve's walkway. The wooden stairs and iron handhold to the observatory inside the dome itself still in perfect condition after all these years. The black iron railing had been touched by many hands of the famous. Sadly, the observatory door was locked. I consoled myself with the spectacular view of the observatory grounds. That should and would have been my highlight if only I had been able to see the inside of the observatory where Struve would have spent night after night observing. An observatory has a way of affording one a glimpse into the observer's heart and soul. In that way I was able to able to feel his presence, smell his working books, walk in his footsteps …

Struve cataloged over 3,000 double stars, most of them new discoveries, which he published his 1827 double-star catalogue, *Catalogus novus stellarum duplicium*. In 1835 he began to measure the parallax of the star Vega (α Lyrae). He selected it because its brightness and large proper motion suggested that it might be near Earth.

In 1830 Czar Nicholas I set aside land in the Pulkovo Hills outside St Petersburg Russia as the site for a new astronomical observatory. He selected Struve for the commission responsible for its construction. When the new Pulkovo Observatory opened in 1839, it could boast a telescope with a 76 cm (30-inch) classic Fraunhofer doublet objective lens. It was considered the best-equipped observatory in Europe for nearly three decades.

Although Struve continued observing binary stars, he now moved into practical astronomy, in the form of geodesy. The observatory's staff made numerous measurements of geographic points in Russia to compile information necessary for road building, railways, and military needs. In 1845 Struve helped found the Russian Geographical Society. After his death on 23 November 1864 his son, Otto Wilhelm Struve, continued the Struve dynasty in Russian astronomy; his directorship of Pulkovo Observatory began in 1858 and lasted until 1899. To honour his career, the asteroid 768 Struveana is named after him.

The early 19th century was the great era of geodesy, the measuring of meridian arcs in many parts of the world in order to establish the Earth’s exact shape and size. Struve supervised the measurement of the Russo-Scandinavian arc. It stretched from the Black Sea to the Arctic Ocean. This geodetic network of 265 triangulations was established between 1816 to 1855, which was named after him. It stretched over 2,820 km from Ukraine to Norway and covered 1/14 of the circumference of the Earth. The Struve Geodetic Arc helped to establish the exact size and shape of the Earth. Its accuracy was confirmed by Satellite-based techniques in the 20th century.

Today the Struve Arc goes through ten countries. Thirty-four triangulations out of 265 are still preserved and are included in the UNESCO's list of protected sites. Two of them are in Russia — Mäkipällus and Z-point on the island of Hogland in the Gulf of Finland.

I was surprised to learn that most of the astronomers and their families had lived on the grounds and were buried in the cemetery situated not far from the main building.

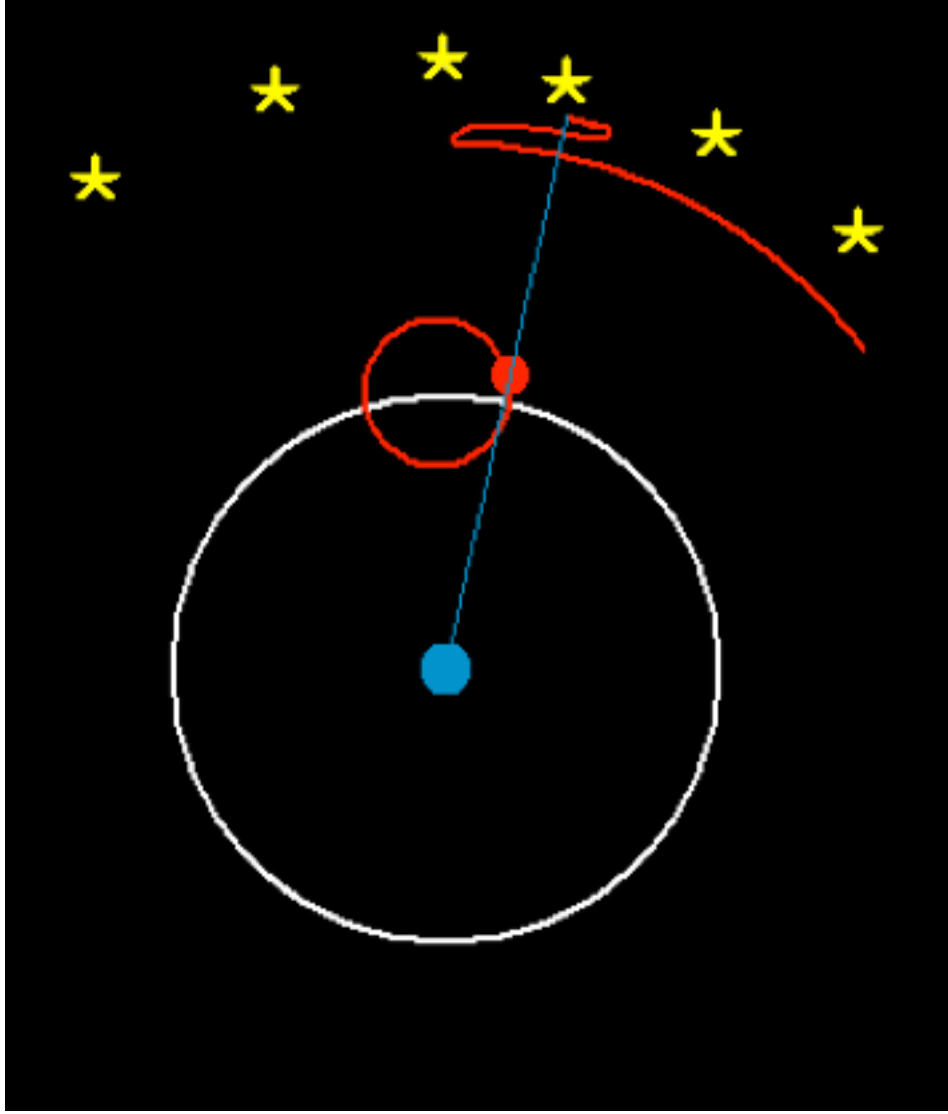
My visit to Pulkovo was running out, so I grabbed my guide by the hand and indicated that I wanted to go to the cemetery to see Struve's grave. I stood in amazement. It is a cemetery with a difference: among thick scrubs with a forest feeling is a multitude of old graves, some covered with moist moss. The graves, most of them with lovely flowers against the stones bear not only the names of astronomers but also information about what they were famous for, along with a picture of the person.

The lady's anguished look told me she could not remember or find Struve's grave, as she threw up her hands in the air! I was disappointed. And there was no way I could help her, as each grave told its story beautifully — in Russian!

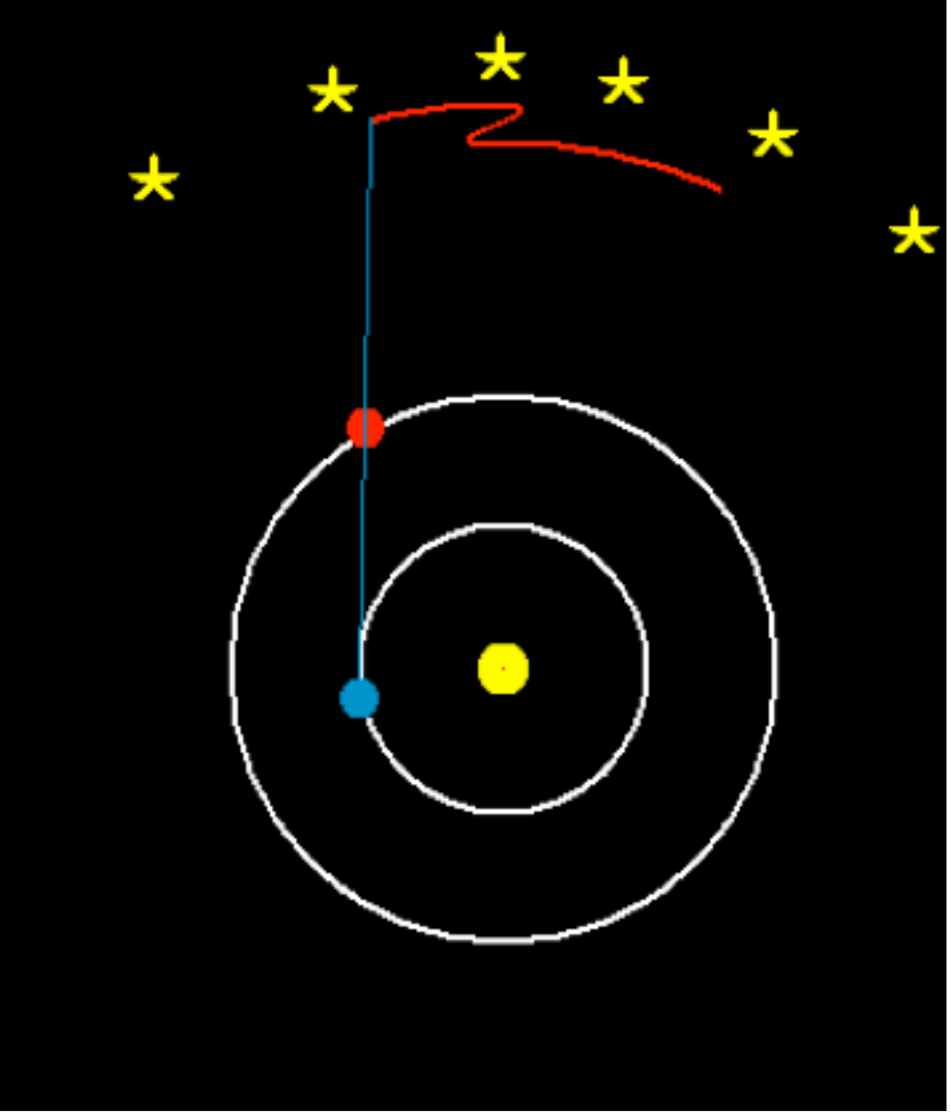
She pointed to an area and gestured that the grave must be somewhere "over there"! Many of the stones were covered in moss, the words long ago washed away by time and nature. Struve had died in 1864. I was gratified when I found that one of my photos captured an image of his grave, (somewhat out of focus) shown by the small white arrow in the picture. I verified it on the Internet after I returned home.

Even though I left Pulkovo Observatory not feeling entirely fulfilled, it was nevertheless a visit I will never forget.

Why Copernicus won

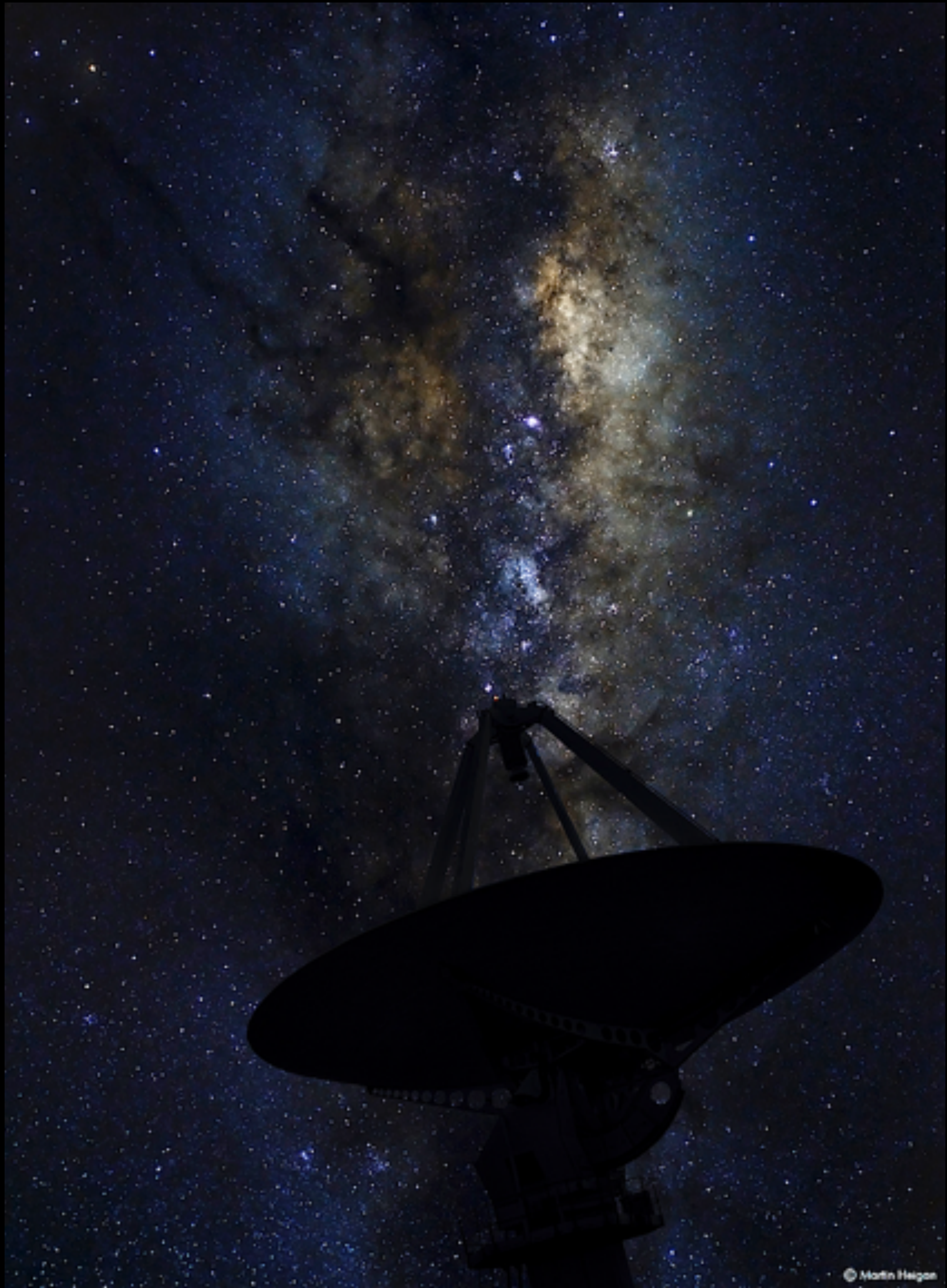


Ptolemy's geocentric model with planetary retrograde motion described by an epicycle (red circle) on a deferent (white circle). Animated gif here.



Copernicus' heliocentric model describing the same retrograde motion. Animated gif here.

Martin Heigan's Astrophotography



I earn a living as a Visual Effects Supervisor and specialise in Motion Capture and 3D Visual Effects for the Film and Television Industry. My passion for photography started in Art School, when I studied Graphic Design and had Photography as a subject.

The great thing about living in Southern Africa, is that unspoilt wide open spaces, dark skies and breathtaking wildlife is always just a road trip away.

I am interested in many different aspects of Nature, and strive to photograph and study it from extreme close-up Macro Photography and Photomicrography, to Landscapes, Wildlife and Astrophotography of the observable Universe in Narrowband.

You can view a panorama of my Flickr images here.

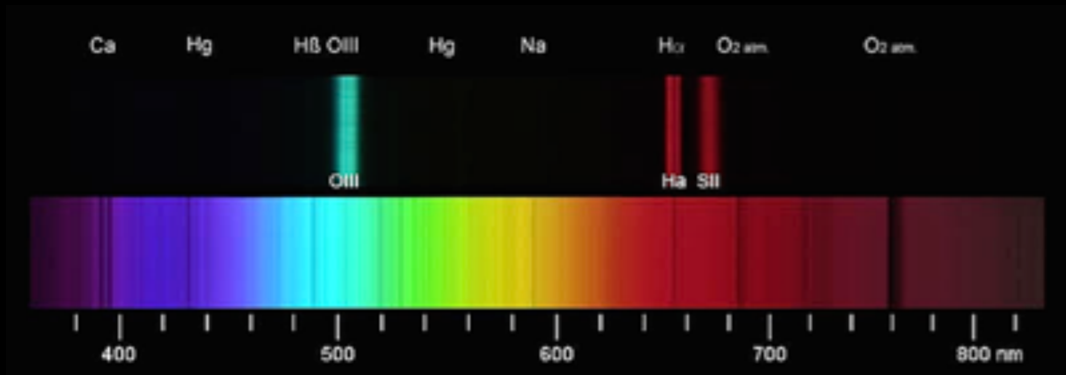
It is important to distinguish between what photometry tells us and what we learn from spectroscopy. The former is a record of the amount of electromagnetic energy we detect in an object. Spectroscopy analyses what causes that energy in the light.

Stars are chemistry labs: they make the atomic elements that in turn make us and everything else in the physical universe. Each chemical element emits electromagnetic energy (light to us) at a unique wavelength in the electromagnetic spectrum. The *emission* spectrum of a chemical element refers to the frequencies of electromagnetic radiation emitted by an atom transitioning from a high energy state to a lower energy state. The energy of the emitted photon is equal to the energy difference between the two states. The exact wavelength that a chemical element emits at is called an emission line. Hydrogen is the most common element in the Universe, and emits in the red part of the spectrum, slightly towards infrared.

The standard narrowband wavebands used in astrophotography are *Hydrogen-alpha* (Hα) at 656.3nm, *Oxygen III* at 500.7nm, and *Sulphur II* at 672.4nm.

When imaging with a DSLR, a good light pollution filter is needed to block the nearby light that we don't want to see, and pass the wavebands that are useful to our understand of what's actually happening in the objects. For example, a broadband light pollution filter enhances certain critical emission lines:

- OIII (496, 500nm)
- H-beta (486nm)
- NII (654, 658nm)
- Hα (656nm)
- SII (672nm)



There are two types of lines in a spectrum. *Absorption lines* are caused by atoms capturing electrons in one of their outer electron shells. The energy of the light is used to nudge the electron to a higher-energy orbit and the photon vanishes. It is absorbed.
Emission lines do the opposite. An electron spontaneously drops down from a higher orbit to a lower one. It emits a photon in the process, which we see as a bright line in a spectrum.

If astronomers seem to be rather keen on studying certain tiny narrow wavebands in a big long spectrum that has many to choose from, there are good reasons for it. Wavebands like Hα, Hß, CaII, SII, or OIII have the helpful property of being comparatively bright and hence easily detected. They are good starting points for someone learning the ropes of spectroscopy, and later on, what spectrograms tell us about the stars and nebulae.

These wavebands are so bright because they emanate from objects passing through critical phases of their evolution. For example, the Oxygen III lines 495.9nm and 500.7nm emanate from gas at a temperature of a few thousand Kelvin and density of fewer than 100 atoms per cubic centimetre. Those are typical conditions in planetary nebulae, which are the cooling, expanding remnants of gas ejected from a star in its last gasps of active life. But those same temperature and density conditions also exist in molecular clouds that are gravitationally contracting into dense cores that will one day fuel baby star clusters.

How does one know what O III lines really tell us? Planetary nebulae are the end states of a star's life. Those stars underwent a long phase in which they fused helium in the core into carbon and oxygen. Lots of those chemicals were brought to the surface, where they cooled down to the temperatures that emit O III light. Collapsing molecular clouds are very cold and have very little or no oxygen. Ergo, O III in an object identifies it as a planetary nebula. Observing astronomers often have an O III filter in their optical toolkit, which they use as a way to see tiny, faint planetary nebulae in their fields that they could not see otherwise.

This is just one example of how spectral lines help us pinpoint a feature in a celestial object we would have no way of knowing without it. Spectral lines are the visual encyclopaedia of the way the universe works.

M8 Lagoon Nebula star-forming nebular complex in Sagittarius

Imaged in the Hα, S-II, and O-III bands, the red in this picture is from H-Alpha (Hα) emitted when a hydrogen electron loses energy in the 3rd orbital and emits a 656nm IR photon as it drops to the 2nd orbital. Hα is emitted by many emission nebulae. In the Bohr model of the atom, The set of transitions from $n \geq 3$ to $n = 2$ is called the *Balmer series* and its members are labelled by Greek letters:

- $n = 3$ to $n = 2$ is called H-alpha or Hα.
- $n = 4$ to $n = 2$ is called H-beta or Hß.

The blue light is from doubly ionized Oxygen ions (O2+) at 500.7nm.

TECHNICAL INFO:

•Optolong SHO Narrowband filters:
•OIII line 500.7nm (6.5nm width)
•H-Alpha line 656nm (7nm width)
•SII line 672nm (6.5nm width)
•William Optics Star 71mm f/4.9 Imaging APO Refractor Telescope
•QHY163M Cooled CMOS Monochrome Camera
•Guiding in Open PHD 2.6.3.
•Image acquisition: Sequence Generator Pro.
•QHY Sensor Sensitivity:
•Gain: 120
•Offset: 35
•Imaged at -25°C
•2 Stage CMOS Cooling
•Narrowband Acquisition time:
•S = 32 x 300 sec. 16bit FITS.
•H = 38 x 300 sec. 16bit FITS.
•O = 38 x 300 sec. 16bit FITS.

Champagne flow of cooling Hα gas dissipating into lower-density field medium; the Hα will dissipate into the disc medium.
Outflow from H36 excitation cools O-III emitting gas until excitation energy is too low for emission. When the temps reach the 10,000 K Hα emission regime the gas glows in the far red/near-IR. Here the transition is abrupt as the outflow moves rapidly into a low-density gas regime. There it cools to ~10,000 K Balmer Hα emission temperature.
Excess H36 gas mass and radiation/stellar jets are expanding H36's natal cloud outward where it compresses cold dense gas (the "Lagoon"). When it slows to subsonic speed it can be revectored by the cloud's weak magnetic field lines, which are then compressed and hence increase in velocity. Here the flow direction is clockwise. toward the magnetic S pole. The white dashed lines highlight a large but weak bar magnet whose gases align like iron filings around small bar magnet. The field lines act as a gas/dust transport mechanism redistributing excess mass to low-density regions.
Herschel 36 (H36) massive star cluster presently <1 Myr old. By the end of its formation/expulsion period ~10 Myr it will rival NGC 6530 in mass & population.
NGC 6530 is a massive ~3 Myr cluster embedded in natal gas hot enough to emit HII & O-III radiation.
Dense gas/dust pockets may/may not form secondary clusters depending on their mass and core density.
Champagne flow
Warm-hot O-III rich gas expanding from NGC 6530 encounters a nimbus-like overdensity of dust-rich cold gas. At the yellow-red shock front tiny vertical streaks indicate rapid dust-gas heating/compression. A small pocket of shock-induced star formation will result in a modest cluster of a few to a few dozen low-mass <M☉ stars. We sometimes see these as asterisms characterised by small numbers, irregular structure, and similar magnitudes. The shadowy cloud inside will eventually ablate into dusty chaotic pockets too small to self-bind.
A <1 Myr proto cluster hidden behind intervening dust here has ±1,000 low-mass pre-main sequence protostars in formation, detectable only in X-ray emission.
Shock front produced when hot gas expulsion from ~3 Myr cluster NGC 6530 moves into lower-temp, lower density ambient medium. Yellowish S-II emission indicates gas temps ~10,000 to 20,000 K. S-II emission here is enhanced by thermal siliceous dust destruction. Over time this shock front will produce low-mass stars.
© Martin Heigan

Rosette Nebula (NGC 2237) in Hydrogen-α 656.3, Sulphur-II 672.4 nm, Oxygen-III 500.7 nm.

Rosette Nebula in the Hubble Palette in Hydrogen-α - 656.3nm, Oxygen-III - 500.7nm, Sulphur-II - 672.4nm.

The interesting thing about the two Rosette images, is that it shows the difference by processing the same data in different ways, and working with the Hubble Palette (HST) compared to a different channel mix in the SHO Palette (to lift out a specific element more clearly). You will notice that when you concentrate on highlighting only a specific part of the spectrum, some subtle details are lost in other wavelengths, but the element that you are concentrating on stands out very clearly. The purpose of an image determines the processing path, and in popular astronomy the aim of the image is often simply to be a pleasing, even dramatic picture. However, for this image I wanted to draw attention to the "hole" surrounding the NGC 2244 young star cluster. As the stars light up in a young cluster the stars' UV radiation is powerful enough to expel the gases not used in star formation. Here the ejection phase is in its early stages, at about 1–2 Myr. By 10 Myr the Rosette will have been dissipated into the galactic medium, leaving behind a brilliant NGC 2244 looking like a distant Pleiades.

The Rosette Nebula is a large, spherical H II region located near one end of a giant molecular cloud in the Monoceros region of the Milky Way galaxy. The open cluster NGC 2244 (Caldwell 50) is closely associated with the nebulosity, as the stars formed from the nebula's matter.

The cluster and nebula are about 5,000 light-years from Earth and measure roughly 50 light-years in diameter. The radiation from the young stars excite the atoms in the nebula, causing it to emit radiation in the form of nebular emission at specific spectral lines that we can image.

IC 410 / NGC 1893 star-forming complex

The faint emission nebula IC 410 in Auriga features two remarkable inhabitants of the cosmic pond of gas and dust, known as the tadpoles of IC 410. Partly obscured by foreground dust, the nebula itself surrounds NGC 1893, a young galactic star cluster that formed in the interstellar cloud about 4 million years ago. The intensely hot, bright cluster stars energise the glowing gas. Composed of denser cooler gas and dust, the tadpoles are around 10 light-years long and are in the self-gravitational contraction phase of early protostar formation. Sculpted by winds and radiation from the cluster stars, their heads are outlined by bright ridges of ionised gas while their tails trail away from the cluster's central region. IC 410 lies some 10,000 light-years away.

TECHNICAL INFO

- GSO 6" f/4 Imaging Newtonian Reflector Telescope.
- Baader Mark-III MPCC Coma Corrector.
- Garmin SkySync GPS Accessory.
- Orion Mini 50mm Guide Scope.
- Orion StarShoot Autoguider.
- Celestron AVX Mount.
- QHYCCD PoleMaster.
- Celestron StarSense.
- Canon 60Da DSLR.
- Aurora Flatfield Panel.
- Hubble Palette (HST):
- Hydrogen-α - 656.3nm
- Oxygen-III - 500.7nm
- Sulfur-II - 672.4nm
- Baader Planetarium 7nm Ha Narrowband filter.
- Baader Planetarium 8nm SII Narrowband filter.
- Baader Planetarium 8.5nm OIII Narrowband filter.

Rho Ophiuchi cloud complex

Rho Ophiuchi is a dark nebula of gas and dust that is located 1° south of the star ρ Ophiuchi of the constellation Ophiuchus (close to the red supergiant star Antares). Fine dust illuminated from the front by starlight produces blue reflection nebulae. The atoms of gaseous clouds that are excited by ultraviolet starlight produce reddish emission nebulae. Back-lit dust clouds block light and appear dark. Antares (a red super-giant star, and one of the brighter stars in the night sky), lights up the yellow-red dust clouds. Rho Ophiuchi lies at the centre of the blue nebula. Interstellar clouds are even more colourful than we can see in visible light, emitting light across a large portion of the electromagnetic spectrum.

TECHNICAL DATA

- Plate scale: 9.95 arcsec/pixel
- William Optics Star 71mm f/4.9 Imaging APO Refractor Telescope.
- William Optics 50mm Finder Scope.
- Celestron SkySync GPS Accessory.
- Orion Mini 50mm Guide Scope.
- Orion StarShoot Autoguider.
- Celestron AVX Mount.
- QHYCCD PoleMaster.
- Celestron StarSense.
- MBox USB Meteostation.
- RoboFocus RF3 Focuser.
- Optolong L-Pro and LRGB filters.
- QHYCFW2-M-US Filterwheel (7 position x 36mm).
- QHY163M Cooled CMOS Monochrome Camera.

Imaged in LRGB:

- L = 34 x 180 sec.
- R = 24 x 180 sec.
- G = 24 x 180 sec.
- B = 24 x 180 sec.

NGC 6144 emission nebula in Ara

This bi-colour narrowband image of NGC 6188 is the result of photographing at several occasions and different locations during the past year, from proper dark sky sites to my pier at home. Deep sky objects like this are the kind of challenge I like most. They push on the limits of my telescope and mount. Hence it is multiply rewarding when I work hard for an image and it turns into an image as visually spectacular as this one. NGC 6188 is located about 4,000 light-years away.

TECHNICAL INFO:

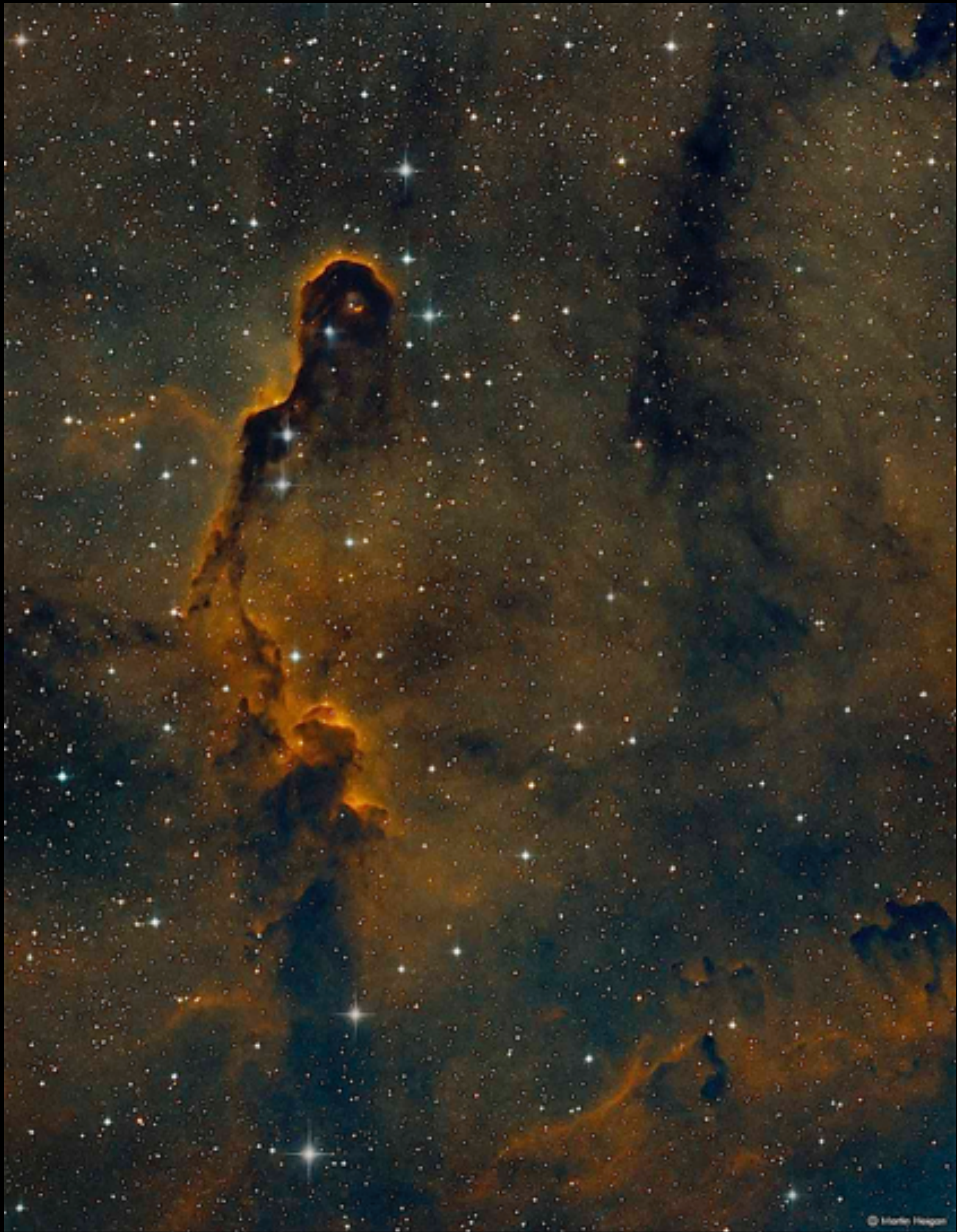
- Plate scale: 3.57 arcsec/pixel
- 64 x 600 sec. 7nm Hydrogen-Alpha (Ha).
- 64 x 600 sec. 6.5nm Doubly Ionized Oxygen (OIII).
- William Optics APO Refractor Telescope.
- Exposures at -25°C on my QHY163M.
- Integration time just under 22 hours.
- Calibration frames: Bias, Darks and Flats.
- Astrometry.net ANSVR Solver via SGP.
- Pre-Processing and Linear workflow in PixInsight.
- Finished in Photoshop.

IC 434 emission nebula and Horsehead Nebula (Barnard 33) in Orion is a dark nebula silhouetted against IC 434. The red glow originates from Hydrogen gas predominantly behind the nebula, ionised by the nearby bright star Sigma Orionis. Magnetic fields channel the gases leaving the nebula into streams, shown as streaks in the background glow. A glowing strip of hydrogen gas marks the edge of the massive cloud. The nebula is located just to the south of the star Alnitak, which is farthest east on Orion's Belt, and is part of the much larger Orion Molecular Cloud Complex.

The Horsehead Nebula is approximately 1,500 light-years from Earth. The darkness of the Horsehead is caused mostly by thick dust blocking the light of stars behind it. This stellar nursery contains organic and inorganic gas and dust, including complex organic molecules. The bright blue stars are still surrounded by nebulosity. They are still "young" energetic hot stars. Star colours differ from blue to yellow, orange and red, an indication of the temperature of a star's Nuclear Fusion process. This is determined by the size and mass of the star, and the stage of its life cycle.

TECHNICAL DATA

- Plate scale: 6.55 arcsec/pixel
- William Optics Star 71mm f/4.9 Imaging APO Refractor.
- William Optics 50mm Finder Scope.
- Garmin SkySync GPS Accessory.
- Orion Mini 50mm Guide Scope.
- Orion StarShoot Autoguider.
- Celestron AVX Mount.
- QHYCCD PoleMaster.
- Celestron StarSense.
- Canon 60Da DSLR.
- Guiding in Open PHD 2.6.2.
- Image acquisition in Sequence Generator Pro.
- 24 x 180 sec. ISO 3200 RGB (CLA FITS)
- Calibration Frames:
- 40 x Bias/Offset.
- 25 x Darks.
- 20 x Flats & Dark Flats.
- Pre-Processing and Linear workflow in PixInsight and finished in Photoshop.



IC 1396 Elephant's Trunk Nebula in Cepheus

A cropped narrowband image of the Elephant's Trunk Nebula, a concentration of interstellar gas and dust with-in the much larger ionized gas region IC 1396 in the constellation Cepheus, about 2,400 light-years away from Earth. The piece of the *nebula* shown here is the dark, dense globule IC 1396A; it is commonly called the Elephant's Trunk nebula because of its appearance at visible light wavelengths, where there is a dark patch with a bright, sinuous rim. The bright rim is the surface of the dense cloud that is being illuminated and ionized by a very bright, massive star (*HD 206267*) that is just to the east of IC 1396A. The entire IC 1396 region is ionised by the massive star, except for dense globules that can protect themselves from the star's harsh ultraviolet rays.

The combined action of the light from the massive star ionizing and compressing the rim of the cloud, and the wind from the young stars shifting gas from the centre outward lead to very high compression in the Elephant's Trunk nebula. This pressure has triggered the current generation of protostars.

TECHNICAL DATA

- Plate scale: 2.02 arcsec/pixel
- GSO 6" f/4 Imaging Newtonian Reflector Telescope.
- Baader Mark-III MPCC Coma Corrector.
- Celestron SkySync GPS Accessory.
- Orion Mini 50mm Guide Scope.
- Orion StarShoot Autoguider.
- Celestron AVX Mount.
- QHYCCD PoleMaster.
- Celestron StarSense.
- Aurora Flatfield Panel.
- Optolong 36mm SHO filters.
- QHYCFW2-M-US Filterwheel (7 position).
- QHY163M Cooled CMOS Monochrome Astronomy Camera.
- Ha = 24 x 420 sec.
- SII = 24 x 420 sec.
- OIII = 24 x 420 sec.

DRAGONFLY COMPOUND EYES.

BLUE ZIRCON FOUND IN CAMBODIA

My gear setup is a bit unconventional, especially seeing that I enjoy wide-field astrophotography. As I've been doing photography for years, I have a lot of camera equipment that I wanted to utilise with my telescope. The idea was to always at least use one unassisted DSRL with a wider lens and intervalometer, while I am imaging with the telescope and cooled CMOS monochrome camera. I had a custom mounting plate made to give me maximum flexibility.

Before I image a deep-sky object I usually research the target data. This gives one a good indication of what narrowband filters would work best, or if it's better shooting LRGB on the cooled CMOS monochrome camera, or just using a DSRL on the telescope for convenience. I have a pier at home, but don't have the luxury of an observatory, so I always have to set up and tear down. This is an important factor, as time also dictates what one can accomplish in an imaging session. In some cases I image the same target over several sessions, and this is made much easier with plate-solving in the image acquisition software. It also simplifies planning and framing targets, and doing mosaics. Everything down to the exact framing of a DSO can be planned ahead of time.

Processing is a lot of fun, and often takes at least as much time as imaging a DSO. Depending on what you want to achieve, different routes can be followed at this stage. With Narrowband imaging, the way you chose to map the colours (or palette) can give very different results. I often like to image in Ha and OIII, and Synthesise the Green channel with a Ha and OIII combination. If there is enough time, I also image SII, which gives one the ability to process in the standard Hubble Palette used by the Hubble Space Telescope (HST). I prefer the flexibly of the SHO Palette, in which I experiment with the best channel mix to bring out the detail or chosen element that emits at a specific wavelength. It is essentially the same as HST, but as the channel mix ratios aren't set; it allows a bit of creativity.

Ironically, my other imaging interest is astronomy's alter ego, close-in micrography. The dragonfly's astonishing array of tiny lenses shown here was highlighted by the magnifying effect of fresh rain drops. The bottom image is a 3 mm zircon I acquired in Cambodia.

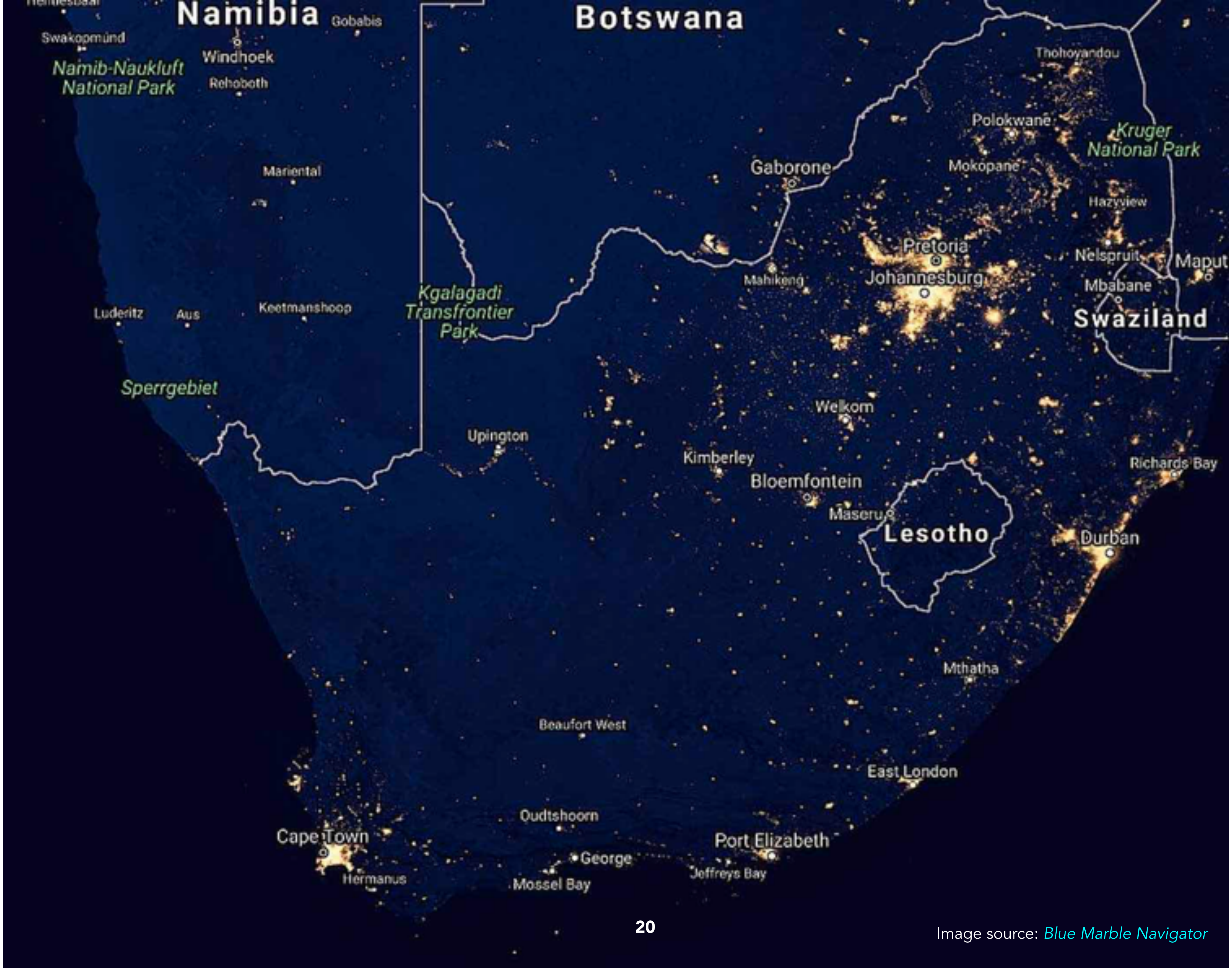


Image source: *Blue Marble Navigator*

How much do clouds brighten the night sky?

An Astro-ph study of night brightness at the Night Sky Caravan Farm at Bonnievale near Cape Town

Summary of paper by Andreas Jechow, Franz Hölker, and Christopher Kyba for the German journal Ecohydrology

Light pollution is a major issue among astronomers these days. Burgeoning urban areas and the ubiquity of electric lighting makes it increasingly difficult for amateurs to find truly dark skies. Professional astronomers are forced to set up observatories in remote locations to avoid the skyglow which can adversely affect their observations. A September 2018 paper published by *Jechow et al.* of the Leibniz Institute Helmholz Centre in Potsdam, Germany, suggests that even observations under seemingly clear skies can be adversely affected by cloudy conditions over distant cities.

Light pollution affects more than visual and imaging astronomers. Artificial lighting can disrupt plants and animals which rely on diurnal cycles. When sea turtles hatch from their eggs on a beach at night, they are naturally drawn towards the ocean because the moonlight reflecting off its surface makes it brighter than nearby beaches or wooded areas. Housing developments in seashore communities which install bright lights can cause the baby turtles to wander inland towards dangers the turtles do not instinctively understand.

Jechow, A. et al 2018: *How dark can it get at night? Examining how clouds darken the sky via all-sky differential photometry*. *Ecohydrology*, Leibniz Institute of Freshwater Ecology and Inland fisheries. Helmholtz Center Potsdam, German Center for Remote Sensing, Geosciences GFZ. Open access on *Astro-ph*.

Determining how much light pollution is present in an area changes over time, as well as how it changes, is important to understanding how it affects the environment. Astronomers have long been at the forefront of light pollution research, but in recent years have been joined by more and more scientists across a range of disciplines. They work together as cross-disciplinary common-interest groups to study the effects of light pollution. The seemingly bottomless reservoir of volunteer citizen-scientist collaborations like *Globe at Night* also gather data for the professional community.

Measuring sky brightness

One area of light pollution research which astronomers have neglected is the effects clouds have on light pollution. Since cloudy skies are no good for observing, scientists initially did not bother to gather data on those nights.

Clouds, however, can significantly affect the amount of light at night even if they are not visible directly overhead. In rural areas, clouds appear dark when they block light from the moon and stars. In urban areas, however, clouds enhance the effects of light pollution when they reflect artificial lights from the ground.

Most commercially available sky quality meters (SQMs) employed to predict night sky brightness and make measurements at zenith using only one spectral band. There is only scattered data available that tells us how the brightness changes with wavelength or altitude.

Now, Jechow et al. 2018 have examined the effects of clouds on artificial light at night (ALAN). The team used off-the-shelf commercial cameras to photograph the night sky during cloudy and clear nights. They set up cameras with fisheye lenses in rural Germany and in South Africa in locales

Differential Photometry

The team adapted differential photometry used in variable-star studies to compare the pictures of the cloudy and clear night sky. When differential photometry is used to measure the brightness of variable stars, it is measuring point sources. Transient noise from aircraft, satellites, or even cosmic rays is readily detected and nulled out. The Jechow team extended the basic principle to compare differences in the brightness of extended surfaces — in this case all-sky images acquired under cloudy conditions and under clear skies.

Fig. 1 to the right shows all-sky images collected at a Bonnievale, South Africa test site. Skyglow is much more apparent in the cloudy images because the clouds reflect light back to Earth. The left and middle image columns show how the team measured the brightness differential between cloudy versus clear sky. The image column marked "difference" shows the clear sky's brightness subtracted from the cloudy sky's brightness. While the Milky Way stands out vividly under the clear sky, in the "difference" image it is diminished from the skyglow bloom caused by clouds. The Jechow team calculated the colour-correlated temperature (CCT) of the sky by comparing it with a black body temperature derived from the Stefan-Boltzmann law. The true brightness temperature was measured by subtracting the observed temperature's black-body component.

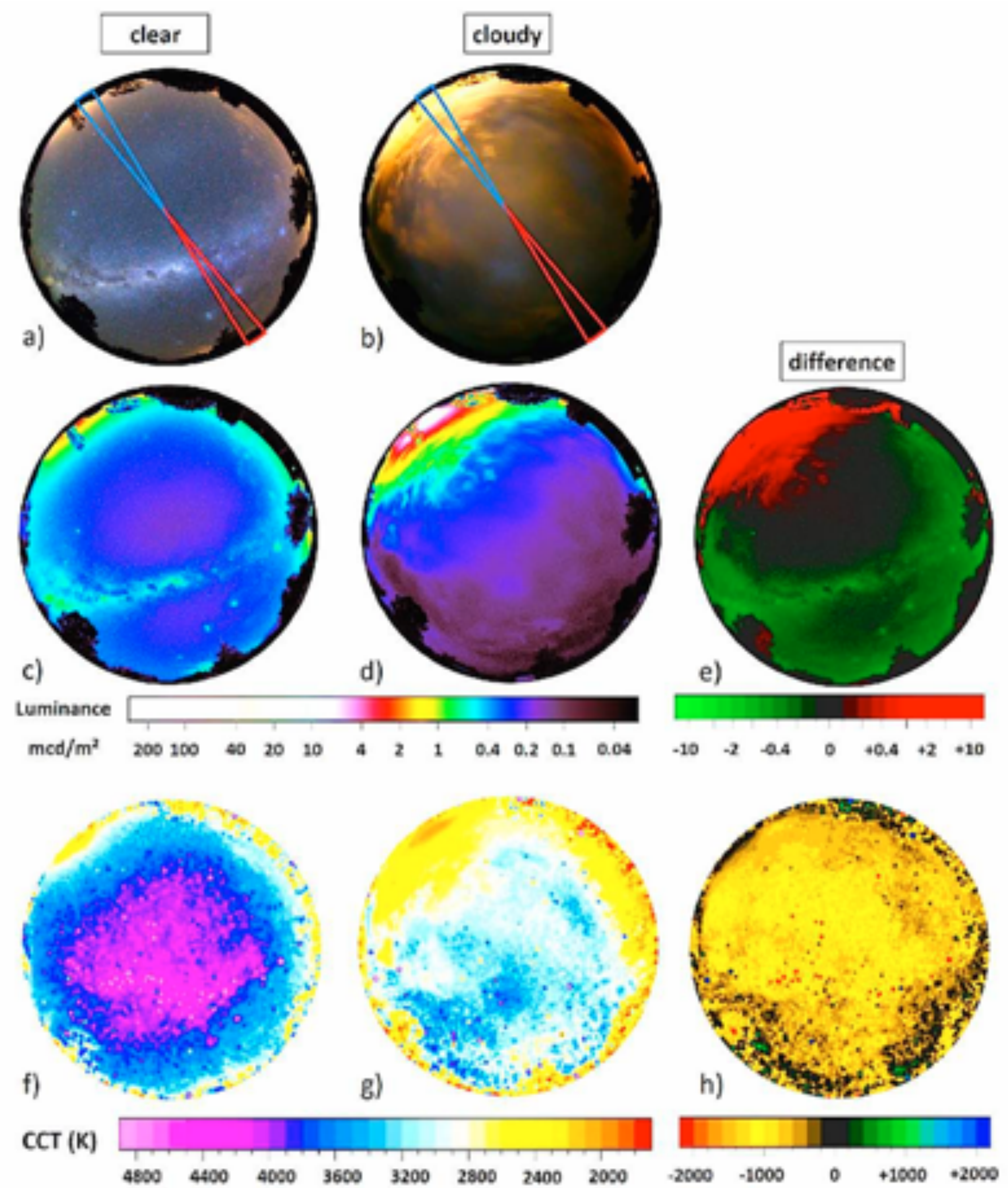
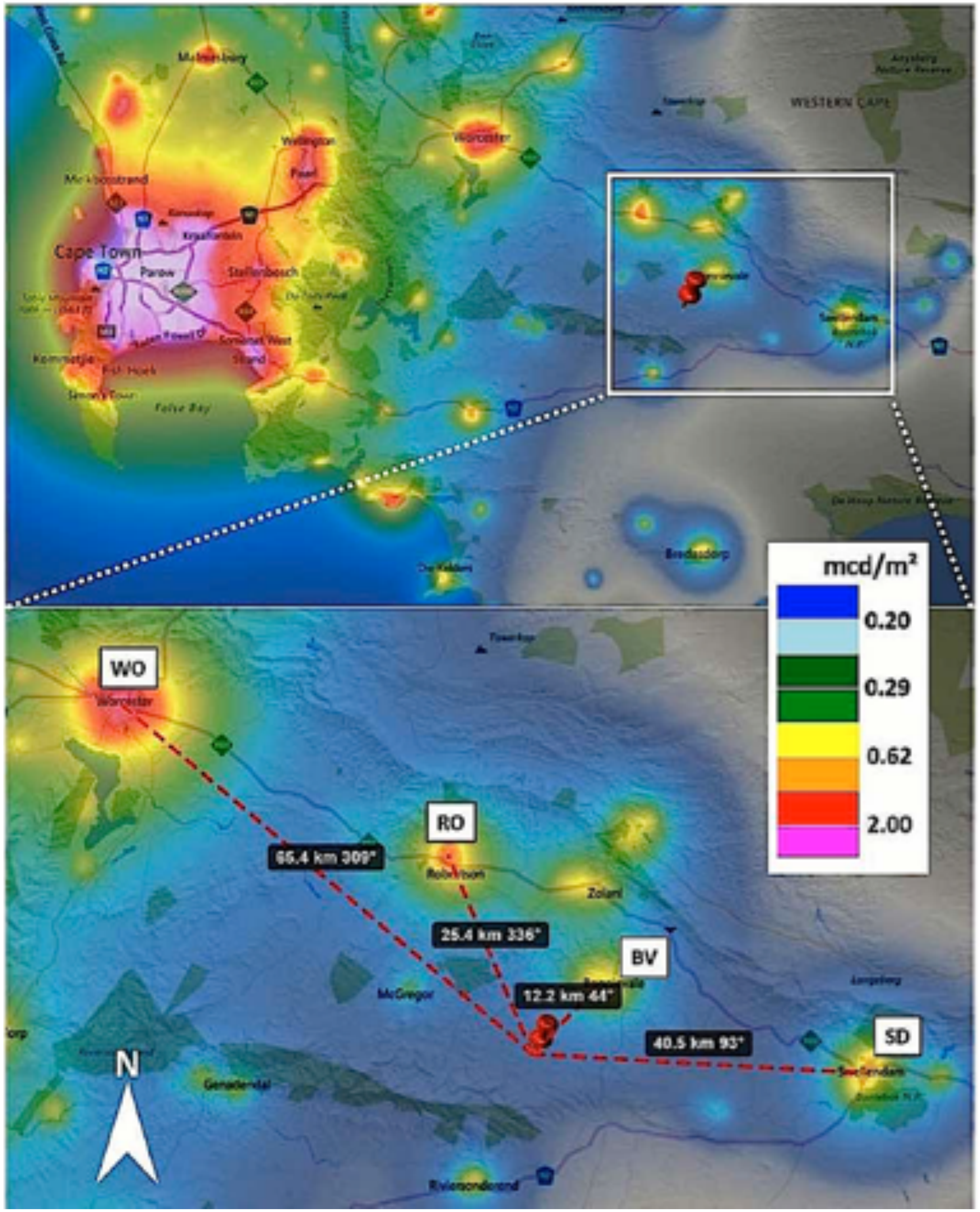


Fig. 1: These images are all-sky RGB images at Night Sky Caravan Park near Bonnievale, South Africa. *Top row*: (*a*) Clear sky on March 15th 2016 at 22:44 local time, (*b*) Cloudy sky on the previous day at 21:50. *Middle row*: all-sky luminance maps calculated from the RGB images for (*c*) Clear night and (*d*) Overcast night. The luminance map (*e*) reveals the difference between the two nights using the Jechow team's subtractive process. *Bottom row*: All-sky maps of CCT calculated from the RGB images for (*f*) a clear night and (*g*) an overcast night. The right hand CCT map (*h*) shows the difference between the two nights after subtracting clear night data from the cloudy night data. *Source: Jechow et al 2018*.



The *Fig. 1* differential map quantifies how clouds decrease the CCT of the sky. The presence of clouds is analogous to redshift in the way it alters perceived wavelengths compared with a rest wavelength. The Jechow et al. study proved that while clouds decrease sky brightness even in areas unaffected by artificial lighting, they drastically increase brightness where light pollution is visible.

This is especially concerning to astronomers because clouds over a distant city can still affect data being collected at a nominally dark observatory. The decrease in CCT also suggests a spectral shift towards longer wavelengths when clouds are present.

The Jechow et al. study validated the use of a CCT subtractive process for quantifying the effects of light pollution. Moreover, resorting to commercial cameras for skyglow research is cheaper and easier compared with the costs of specialised sensors. The study opens a new door for interdisciplinary collaboration. The effects of light pollution reach across many disciplines, from astronomy to ecology to human health. Here is a case of interdisciplinary thinking could lead to darker skies.

Ed. note: If you want to find out how bad light pollution is where you live, use this interactive map created from the *World Atla*s data or the *NASA Blue Marble Navigator* for a bird's eye view of the lights in your town. Google Earth users can download an overlay also created from the "World Atlas" data. And don't forget to check out the Globe at Night interactive light pollution map data created with eight years of data collected by citizen scientists.

M20 Trifid Nebula by Marc Schafer, Grahamstown

Small mice – big tale

BH 176 and ESO 92-SC05 — two tiny globulars with a big story to tell

Doug Bullis

Cars run out of fuel. So do galaxies. At the Milky Way's present gas consumption (i.e., star forming) rate of 1 to 2 solar masses every year, the Milky Way will run out of gas in 2.6 billion years. That will at least get us across town on the long long road to the big city of Virgo Supercluster, but what happens when the gas tank runs low? Where's the gas station?

Actually, there are two. The far-away one is a quarter of the way to Virgo, and is called *Local Filament*. Local Filament is a very big place and very complex to navigate. So let's tank up closer to home. It's called the *Galactic Stream System* because it has 15 pumps (so far), all named Stream. They dispense fuel blends with names like *Pal 5 Stream* (*1*), *Sagittarius Stream* (*1*), *Arcturus Stream* (*1*), *Virgo Stream* (*1*, *2*), *Magellanic Stream* (*1*, *2*, *3*), *Anticenter Stream* (*1*), *Helmi Stream* (*1*), and a stream whose origins we can't quite figure out which is called (surprise) *Orphan Stream.* That one is so far out there that it forms a giant ellipse larger in every dimension than the entire Milky Way disc and takes f-o-r-e-v-e-r to top up our tank. Another pump, called *Monoceros Ring* (*1*, *2*, *3*), wraps itself around the Milky Way three times and is thought to be the almost digested stars of the Canis Major Dwarf. And we thought putting a Tiger in the tank was such a Big Deal.

There's something a bit odd about where these pumps are themselves filled. Nine of them list their origin as Defunct Dwarf Galaxy, four others say Defunct Globular Cluster, one says it is Possible Progenitor of Styx Stream, and the rest list Big Name celebrity gas bags like Canis Major Dwarf and Large Magellanic Cloud. It says so right there in *Wikipedia* and who's to question Wiki when it comes to reliable source material?

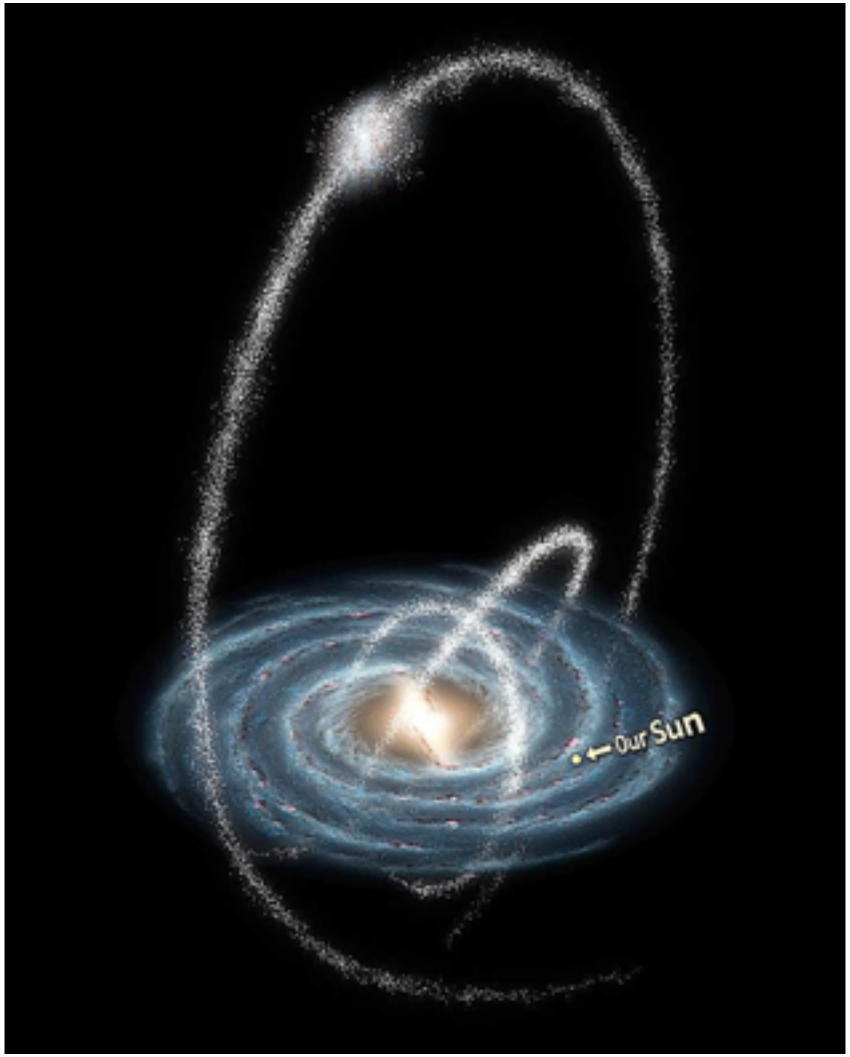
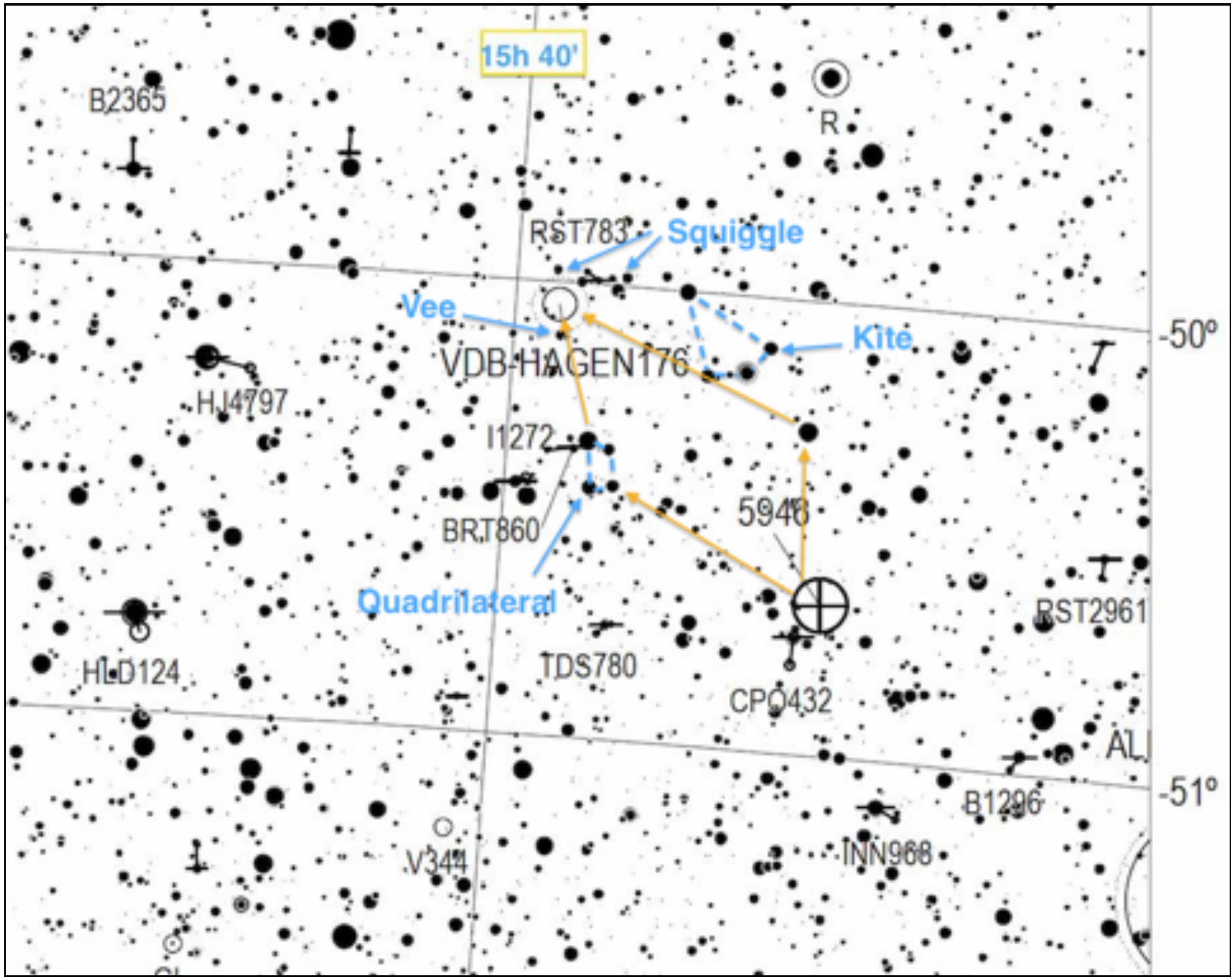


Fig. 1: A sample of three stellar streams around the Milky Way. Such streams form when dwarf galaxies or globular clusters fall into the gravitational well of the MW and are tidally disrupted first into slender arcs streaming on either side of the former galaxy core. M54 Sagg, Pal 5, and probably Omega Centauri are surviving cores. Others are lengthy elliptical streams which can encircle the disrupting galaxy. The Monocerous Ring (not shown) encircles the Milky Way three times.

The problem with all these diaphanous streams eager to get into our gas tank is that none of them actually fill us up where it counts: the stellar disc. Instead, the stars these streams contribute end up in our Galactic halo and thick disc while their meagre contribution of gas ends up cooling our Galactic Corona. (The Corona is the electromagnetic field around our galaxy and the free ions which transfer the currents; the more familiar Halo is the stellar content.) Even worse, gas siphoned from dwarf galaxy streams is cool, on average ten thousand Kelvin while the Galactic corona averages two million Kelvin. I'm not so sure we should rush to the *Astrophysical Journal* with the news of our discovery of a New Law of Thermodynamics, namely "Add cool to warm and you get warmer". So ipso facto, inflowing gas cools our corona, which robs it of energy, which constrains star formation, which means we're not going to no Virgo Supercluster on gas siphoned from space. Can you imagine the gnashing of teeth and rending of garments if a major oil company dispensed energy-*losing* fuel at one of their ghastly examples of function-makes-form architecture?

So here we sit, amateur astronomers swelling with pride at our minimarvels of homebrew glass and TLC, just itching to somehow prove that we, not just those fellows on mountaintops, can actually spot the solution to the mystery of how our galaxy fills its tank. Can we? Let's check out a few possibilities.



ESO 224-8, aka van den Bergh-Hagen 176 (Simbad: BH176), OC Norma

"VDBHA176 is a large very low surface brightness globular cluster. It is 6' across and has a slight brightening toward the middle. The sky here is very busy so the cluster is difficult to pick from the background. Numerous 13–14th magnitude stars are scattered about the face of the cluster. High power did not resolve the cluster. The cluster could easily be overlooked as a general sky glow about a grouping of stars. A photo taken by the ESO Schmidt allowed me to identify the cluster correctly. *Megastar* lists the object as an open cluster and is positioned about 20" east of the correct position." (Andrew Murrell, Ilford NEW, Australia, n.d.)

"Seen at a very low altitude so this globular cluster was difficult, using MegaStar chart and replotted location from William Harris' database of Milky Way Globulars. I saw 5 (13-14th magnitude) stars with a faint background glow about 4' in size. This cluster appears visually more like an open cluster than a globular in the eyepiece." (*Barbara Wilson, Texas USA, 1997*)

"RA: 15h 39m 5.4s, Dec: −50° 03′ 2″, 6 observing sessions March-Apr 2016, Weltevreden Farm, Karoo 31°8587 S 24°4403 E, Intes 6″ and 8″ Mak-Newts 48x – 212x, LVM ~7.3–7.5, trans. 8–10 seeing 7–10. *Finding details:* From m_V 9.6, 1.5 arcmin dia. globular NGC 5946 Norma proceed either (a) 40 arcmins NE to a prominent rhombus of four stars m_V 8.6–10.2, then 32 arcmins along longest side of rhombus to Squiggle, a ragged line of seven 10.5–11.2 stars perpendicular to rhombus vector line; or (b) from NGC 5946 proceed 42 arcmins along 350° line to an isosceles "kite" of m_V 9.2–11.6 stars, then 290° for 33 arcmins to a Squiggle feature. W end of Squiggle has 3 arcmin dogleg of 9.9 & 11.0 stars; ~3 arcmins E of dogleg is m_V 11.1 star w. two m_V 12 stars below left leading to obvious ragged circlet of 6 M_V 12.1–14.2 stars ~4 arcmins dia. MH176 slightly off centre to WSW within Circlet. *Observations*: Brightest BH176 cluster star is 14.6, well w/in range of 8″ scope but spotted only erratically due to Circlet's distraction. In 6″ Mak-Newt faintest stars in circlet near visibility limit & cluster undetectable across ½ hour steady gazing on 4 nights. In 8″ Mak-Newt at 212x, four Circlet stars steady in direct & two irregular in averted. BH176 halo glow seen fleetingly four times in six half-hour sessions across four nights. Cluster presents as barely perceptible evanescence for only 1–2 seconds each sighting, approx. 2 arcmins dia. w.no discernible core concentration as is seen in deep images. BH176 presents similar visual effect as GC Lyngå 7 in Norma or Westerlund 1 Ara. More difficult than any of the Fornax GCs @ m_V 12.6–13.6, NGC 6419 Aquila, or E3 Chamaeleon. *Summary*: nice sizzle. No steak." (*Douglas Bullis, S Africa, April 2016*)

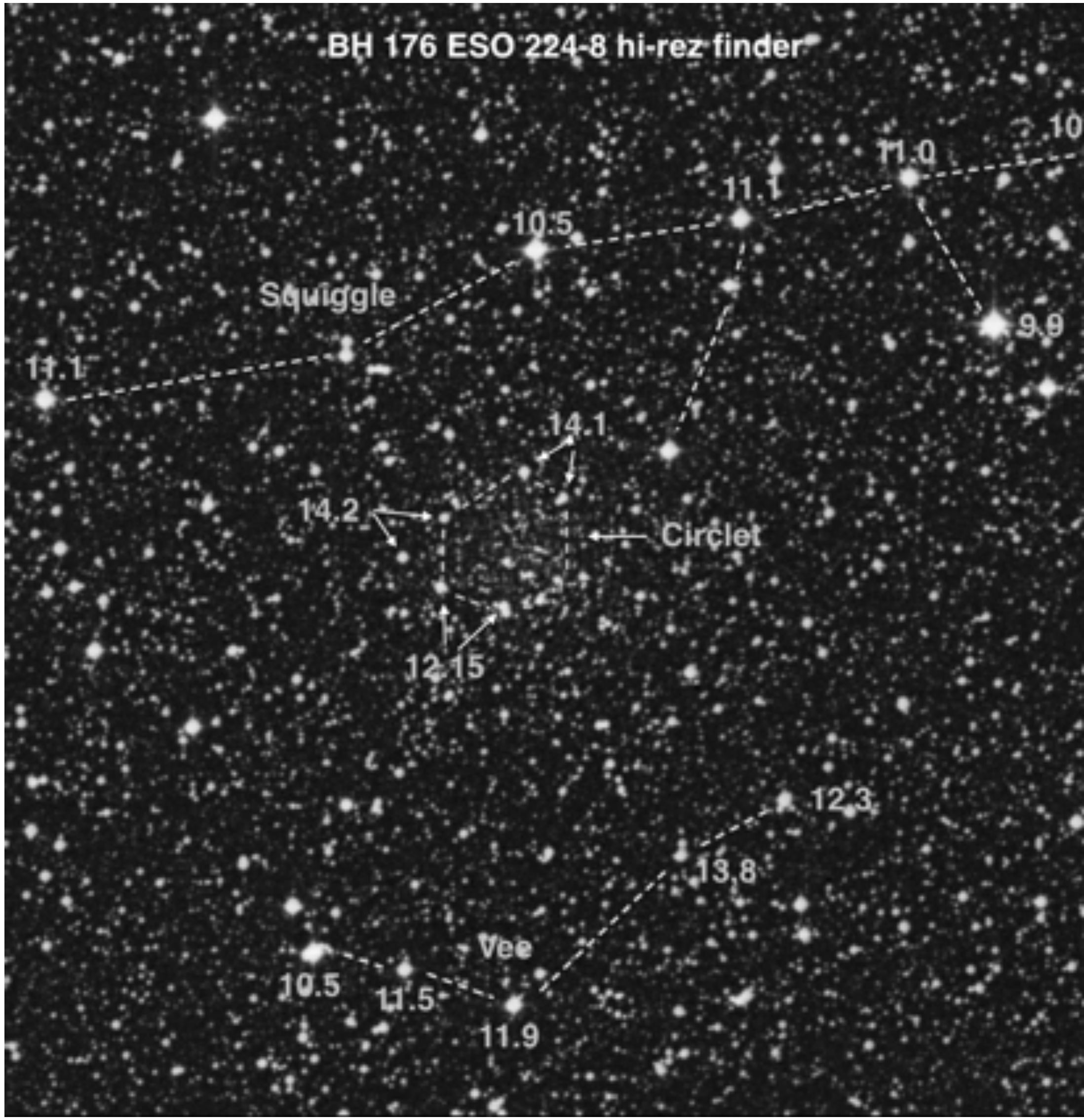


Fig. 3: The trick to confirming BH 176 is looking for a very faint glow inside what appears to be a small open cluster whose keynote stars range from m_V 12.1 to 14.2. As faint as they are, they are still a distraction when surrounding an even fainter one inside.

ESO 092-SC05, OC Carina

So far, I have found no previous amateur community reports of this interesting, very old (>6 Gyr), elusive open cluster near the Southern Pleiades in Carina. This is not surprising given that the cluster was discovered only in 2000. Even in the professional literature only one paper studies it, *Ortolani et al. NMRAS 2008*. ESO* 92-SC05 is one of the least-studied Galactic cluster we come across. It deserves more attention from both communities. Visually, it is the most difficult cluster I have ever observed in an 8-inch scope. Professionally, it is interesting because is sidesteps the known Galactic open cluster parameters with respect to location, kinematics, chemical content, origin, and evolution. In sum, it's a rare bird which conceals itself very successfully from our eyes and algorithms.

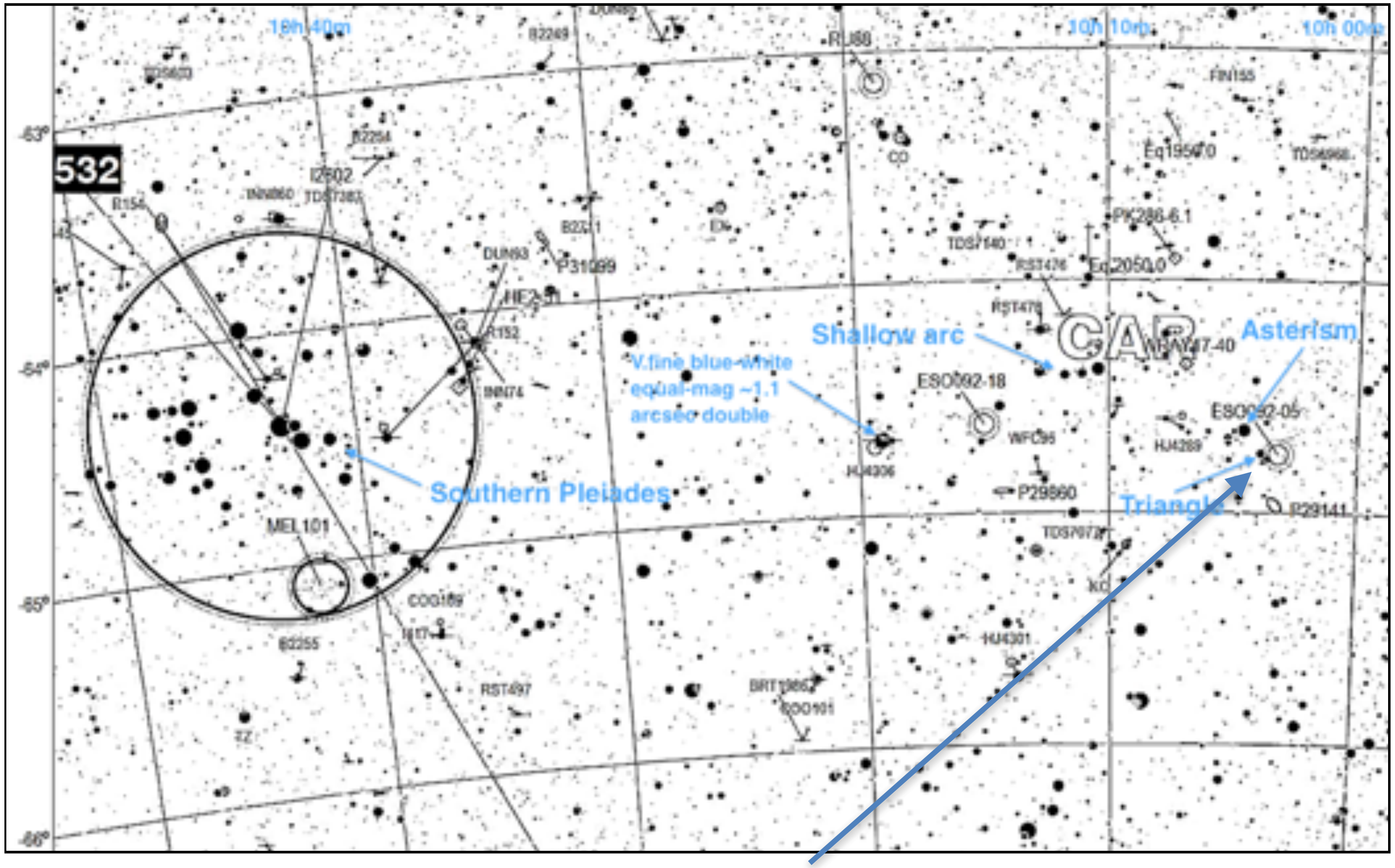


Fig. 4: Wide-field finder for ESO 92-SC05.
Source: *Jose Torrès TriAtlas C* chart 533.

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* ESO is the acronym for the European Southern Observatory / Uppsala Catalog compiled in 1982 from blue plates taken by the 1 metre Schmidt telescope at La Silla, Chile and the US 48" Schmidt at Siding Spring, Australia. The survey shows 18,438 DSOs in 606 fields centred on 5° sections from Dec -20° to -90° and to m_{BL} 21.5. It is sometimes referred to the ESO(B) Catalog because the telescopes recorded images using blue-sensitive Kodak IIa-O plates in combination with a GG 3850 nm filter. For an explanation of the ESO object numbering system see *Lauberts 1982*.

To get there, return to the shallow arc and proceed SW at 315° past a wide M_v 12 pair down to the Asterism marked on Fig. 5 below. Continue 12 arcmins to the Triangle formed by m_v 8.9–10.4 stars. ESO 92-SC05 lies several arcmins due west. What do we find when we arrive?

"Observing report for ESO 92-SC05 10h 03m 14s, –64° 45′ 12″ (Gal: *l* = 286° *b* = –7.50°): Summation of six observing sessions March-Apr 2016, Weltevreden Farm, Karoo, S Africa, 31°8587 S 24°4403 E, Intes 6″ and 8″ Mak-Newts 48x – 212x, LVM ~7.3–7.5, trans. 8–10 seeing 7–10. ESO 92-SC05 is located 4.2° W of the Southern Pleiades and 2.2° E of μ Carinae. Find the shallow arc of 8–10 m_V stars midway between the So.Pleiad. and μ Car shown on Fig 4. To the SE of the arc lies the pretty OC ES0 92-18 reported *here*. ESO 92-18 is visually more luminous than ESO 92-SC05. Seen tremulously in a 6-inch scope, in an 8-inch ESO 92-18's dull round glow resolves into ±10 m_V 14.5–15.5 stars with the white phorescence of abundant stars below visibility.

ESO 92-18 is a warmer-upper for ESO 92-SC05 1.3° to W. The various comparison stars in Fig. 5 help pinpoint ESO 92-SC05. The cluster's brightest red clump stars are m_V 16.5, which at the cluster's metallicity of Z=0.004 puts its red giants in the m_V <14.8 region. Most observers with sub-12 inch scopes will simply have to wait for the 1 arcmin white glow of the cluster to flicker feebly in and out during moments of low scintillation. It was unseeable in my 6″ Mak-Newt, which can see to m_V 14.2 on the best nights. The 8″ revealed a fleeting <30 arcsec m_V 15 glow distinguishable from a faint asterism only by the evenness of its patch. The nearby m_V 14.1–15.0 double shown in Fig. 5 is a great practice object because the cluster is somewhat fainter and larger, but round instead of oblong. The core region of the 400 Mlyr spiral PGC 29141 directly beneath the Triangle asterism is somewhat more visible than ESO 92-SC05." (*Douglas Bullis, S Africa, April 2016*)

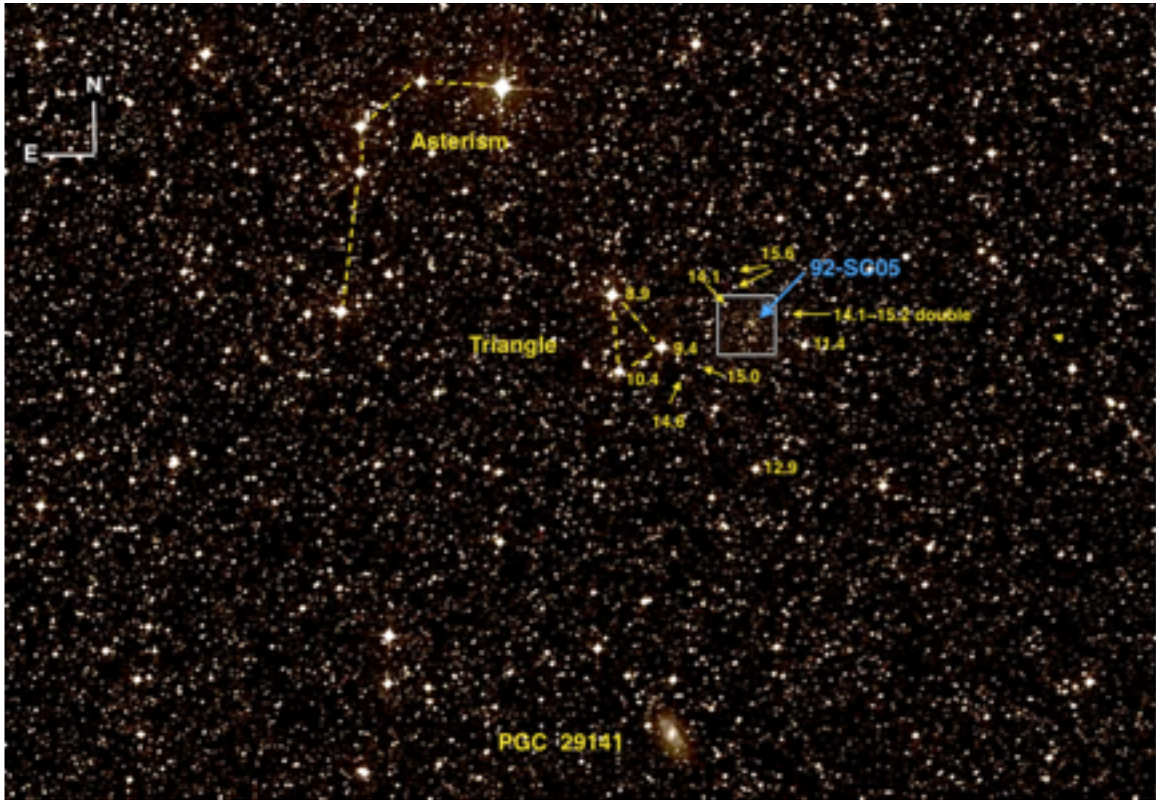


Fig. 5: PGC 29141 (10 03 18.6 –64 58 02.9) is a M_V 13 spiral at z=0.0073 or ~100 million lyr out and is a member of the galaxy bridge between the Hydra and Antlia galaxy clusters.

Disc heating

BH176 and ESO 92-SC05 are astrophysical correlates. Both clusters are a very old >5 Gyr. They are improbably large spatially and in stellar mass given their location in the upper Galactic thin disc. They differ kinematically with their surroundings — BH176's proper motion relative to its surroundings is 24 km s^{-1}; ESO 92-SC05's is 15 km s^{-1} (both prograde). If they were formed in the thin disc like Galactic open clusters, they shouldn't be where they are. Nor would they travel as fast as they are. Indeed, they shouldn't be at all. Yet there they are. Why?

It has been shown by many authors that very old open clusters in the thin disc tend to migrate slowly outward along the Galactic *b*-axis into the thick disc due to disc heating from HVC (High Velocity Cloud) infall and disc star formation. However, it is doubtful that disc heating can move >1,000 $M_{\odot}$ clusters >5° above or below a Galactic disc. Outer disc heating exterior to the solar circle can come from cold High Velocity Clouds (CHVCs) infalling into the disc and shock-compressing to star-forming densities. The cluster Blanco 1 in Sculptor began as a rapid HVC that penetrated into the disc nearly vertically from below, quickly formed a loose star cluster, and kept right on going to its present position 750 lyr above the disc plane and pulling away.

Heating in the inner disc regions comes from Giant Molecular Clouds (GMCs) entering a galaxy disc wave at high velocity but shallow entry angle, breaking up, and forming multiple clusters.

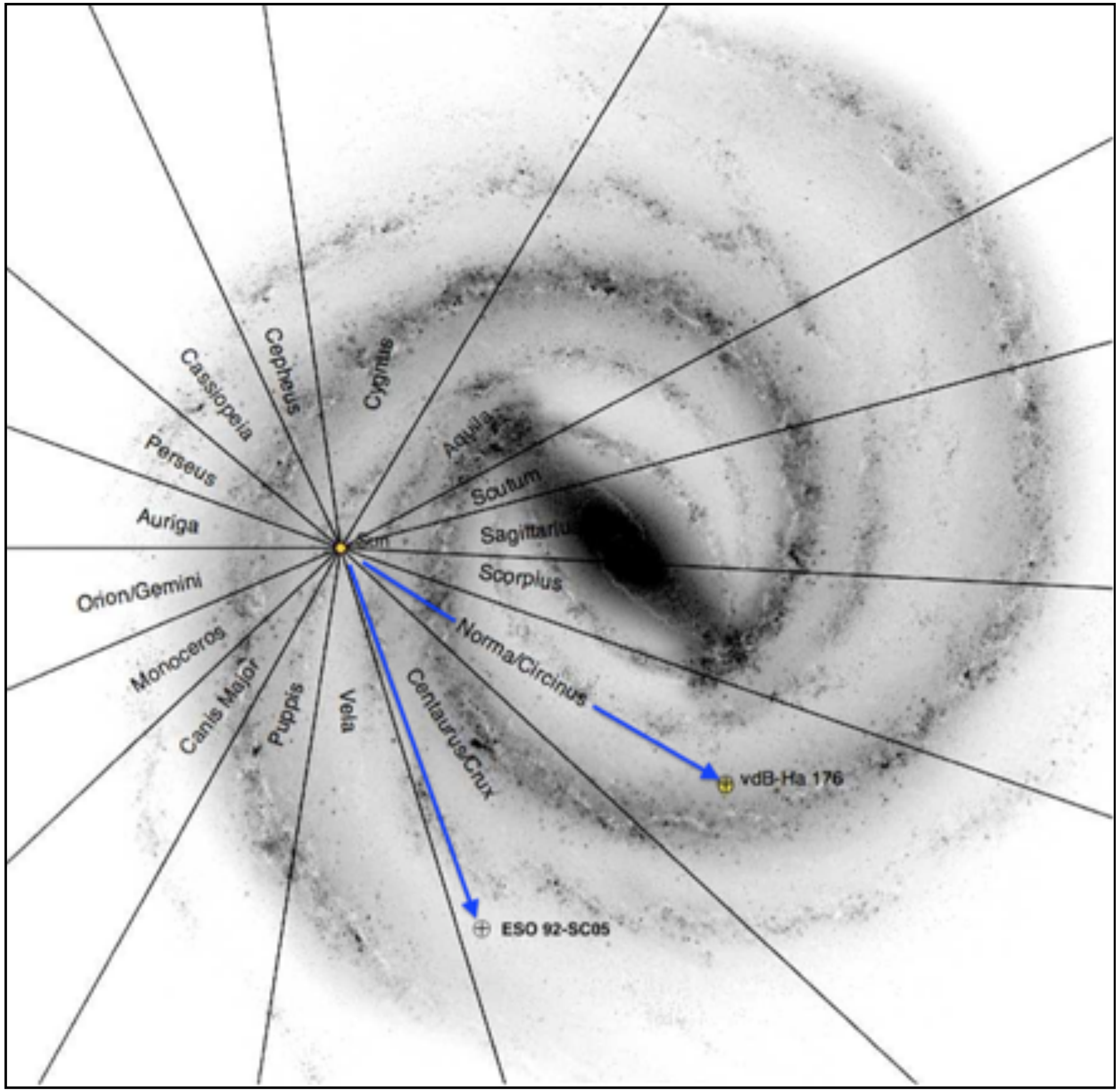


Fig. 6: BH176 and ESO 92-SC05 locations on disc plane. On the *b*-axis vertical scale both clusters are well removed from the star-forming thin disc. Instead they lie in the upper regions of the thick disc, at *b* = 4650 ly above the disc for ESO 92-SC05 and *b* = 3800 ly for BH176.

What does “disc heating” mean?

Because we are located inside of our own Galaxy, it is the only galaxy for which we lack a truly global perspective in a single snapshot. Instead, we must survey the entire night sky to fully understand its structure.

Disc heating in a galaxy is simply the increase in random motions of the galaxy’s stars as a result of internal and external forces. The word “heating” in astronomy does not mean warm to the touch. Instead, it means the density of random motions at a given temperature.

Observations of edge-on galaxies reveal that they are remarkably thin structures, but not infinitely so. Their finite extent perpendicular to the disk plane can be attributed to the excursions that stars take in this direction due to their random motions. Most stars are born in the very thin ~100 pc thick layer of gas in these galaxies. Due to the ubiquity of the gas’s internal collisions, it has little in the way of correlated motions.

Thus, stars acquire their random velocities in later life. Several theories have been advanced for the source of this “heating.” One way to acquire velocity is by gravitational scattering from interactions with more massive objects. We immediately think of close stellar swing-bys in which a more massive star donates part of its angular momentum to a smaller star, speeding it up. but an encounter with a million solar mass molecular cloud does it even better, albeit less dramatically. Similarly, the mass enhancements associated with spiral density waves — swing amplification — can gravitationally scatter stars as it adds to their peculiar velocities. Finally, the heating could be due to an external source, such as a small satellite galaxy colliding with the disc. The energy dissipated in such a collision can “heat” the original stellar population by transferring the small galaxy’s angular momentum to the disc or halo stars where the interaction takes place.

Scattering off giant molecular clouds is a stochastic process, i.e., random, but described by the bell-shaped curve of velocity distribution. Moreover, galaxy discs are riven with resonances. Density waves are resonances we can see, but there are several others. The Inner and Outer Lindblad resonances are invisible but in fact are interfaces between major velocity structures, acting in effect to constrain motions on either side. Our Sun lies very close to a very potent resonance called Co-rotation. That is a zone around the disc where the forward velocity of a parcel of stars matches the forward velocity of the spiral wave itself. Co-rotation circles tend to be internally quiet, rather like the water in a pond beneath the waves that pass over it. Outside or inside co-rotation, a star will receive an energy boost from the spiral wave twice per orbit. When a galaxy’s rotational frequency is close to the star’s random oscillation frequency imparted at birth (for example, a cluster born from a parcel of gas with vertical component moving it away from the disc plane), any random motions the star had at its birth will be amplified by the wave.

A galactic bar is the dominant heating mechanism in most galaxies. Bars exist in about 70% of spiral galaxies, sometimes in gas form so they aren’t visible to our eyes. Several resonant processes are at work in galactic bars that make them short or long radially from the bulge, skinny or fat above and below the disc, slender or wide forward and aft from their centreline.

All these processes can enhance a random star’s motion in whatever direction it was going to begin with. The chances of stars having a vertical component are high, even though the actual value of that motion may be small —1 km/sec, 5 km/sec, or large, >100 km/sec. The end result of dynamical interaction is more stars moving faster. The name for this is dynamic heating. When it happens in relation to stars in a disc, the end result is disc heating. Heating anything tends to expand it. Since galaxy discs liken to a fluid made out of stars and gas, heating it expands it. That means expanding vertically, too, which is why the older a star cluster is, the higher above the disc plan it tends to be. Several mechanisms work to increase disc heating. Of these, the most important is stars being scattered by molecular clouds and spiral arms.

Even globular clusters get into the act. When a globular was born, long before any disc planes existed, the internal dynamics of star cluster birth drove over half the cluster’s mass away within about 10 million years due to winds from hot massive stars which eventually became supernovae. The inner stars responded to gas loss by condensing into a smaller radius. The lightweight outer stars simply evaporated away. Eons later when old globulars began to transit through the newly formed discs, they lost part of their orbital energy to the galaxy disc. Disc crossings by the Milky Way’s globulars have contributed about 4% to the total random motion value of all the stars in the disc. Not much, but it adds up.

A good case study in star cluster disc heating is the cluster Blanco 1 in Sculptor. It literally dropped in from outer space. It arrived as an HVC that penetrated into the disc almost vertically from below, compressed into stars, and is now on its way back out at some 750 lyr above the disc plane. Similarly, the Corona Australis dark cloud is entering the disc in much the same way, from below at high velocity. It too will form a fast-transit open cluster and keep right on going. As clusters like these enter and leave, their gas remains behind, also helping to heat the disc.

Heating in the inner disc regions comes from a very different source: giant molecular clouds (GMCs) entering a spiral density wave at high velocity but a shallow angle. These break into multiple dense cores and collapse into massive clusters. The M8–M16–M17–M20 complex in Aquila and Sagittarius is a 3,000-light year-long collect-and-collapse filament following the GMC playbook of enriching a galaxy disc with cold gas and hot stars.

There are many examples of >5 Gyr clusters lying well into the thick disc. Northern observers can pay a call on NGC 188 and M76 as examples (though NGC 6791 Lyra preferred to stay closer to home). Southern observers have Collinder 261 (Musca), ESO 96-SC04 also in Musca and cataloged by the name *Andrews-Lindsay 1*.

Bonatto et al. (2006) showed that Galactic open clusters older than 1 Gyr can reach heights up to 350 pc (1140 ly) outside the thin disc due to disc heating. The cluster ESO 92-SC05 that we observed earlier in this article is 1.4 kpc (4560 lyr) above the disc plane. This cluster has a total of 1800 ±400 $M_\odot$ — a surprisingly massive cluster given its age. M67, by compare, at 4 Gyr and a known Galactic disc cluster, has a mass of just 724 $M_\odot$.

The differential heating generated by these various processes forms pressure gradients in the disc which transfer thin-disc heat to the thick disc above it. The many disc resonances discussed earlier disperse part of their energy as vertical waves in the thick disc that are analogous to vertical waves in the Earth's atmosphere. While atmospheric vertical waves manifest visibly in herringbone clouds and lenticular mountain waves, in the thick disc the waves are called corrugations and have only recently been investigated.

How do all these interesting properties actually work out in physical objects we can examine? Let's look again at those two remote disc clusters placidly doing not much in a part of the Galaxy where they can't have been made?

BH176 is one of just thirteen >6 Gyr metal-rich clusters known in the Milky Way, [Fe/H] ≥ –0.24 (0.58% $M_\odot$). It is 15.2 ± 0.2 kpc (49,550 lyr) from MW core, 1.5 times more distant than the Galactic bar tip in Norma where the bar abruptly swerves leftward (CCW) into the Perseus Arm. BH176 is 7.0 ±0.5 Gyr old based on α-element abundance of red clump stars [α/Fe] ~0.25 dex (dex as used here is the mean of [Mg/Fe], and [Ca/Fe]). It is spatially and kinematically consistent with Monoceros Ring with proper motion V_h = +15 km s^{-1} to Galactic disc rotational velocity. *Sharina et al 2014* in *Gemini spectroscopy of the outer disk star cluster BH176* propose that BH176 originated as a massive star cluster after either (a) the high velocity infall of a massive gas cloud into the thin disk, or (b) as a satellite dwarf galaxy now completely absorbed into the Galactic disc. This implies a shallow entry angle, which is consistent with BH176's velocity nearly paralleling the thick disc rotation.

ESO 92-SC05 is a >6 Gyr old OC orbiting in the outer thick disc. Its metallicity [M/H] is −0.7 ±0.2, which makes it one of the metal-poorest clusters in the Galaxy. *Chen et al. 2003* point out that open clusters with [Fe/H] < −0.5 are extremely rare. At a distance of 11.4 ±1.0 kpc (37,160 lyr) from the Galactic centre (10.9 kpc or 35,530 lyr from us), ESO 92-SC05 cannot be a Galactic cluster. It must be an accreted open cluster from a now disrupted dwarf galaxy. The problem is: which one? Or rather, which stream of an accreted and now identitiless dwarf galaxy? The evidence is inconclusive.

Faraway nearby

As subtle, inconspicuous, and remote these clusters are, they have in their own tiny way contributed to the heat budget of our Galaxy. They are a little like red blood cells in living blood: tiny, but vital. In both examples their anonymity is just as necessary to the health of the whole as the spectacular spiral arms and skeletal bones are to their respective bodies.

Fig. 7: This inverted-colour image of an edge-on galaxy illustrates the effects of inner-halo heating from particle winds from the galaxy bulge along poloidal (from the poles) magnetic field lines. In turn outer disc warps are induced by dynamical interactions within the spiral arms. Galaxies seem fated to be wobbly affairs, and aesthetically seem to be all the better for it.

Magnetic unattraction

Neutron star Swift J0243.6+6124 has a very strong magnetic field which prevents the accretion disk from making it all the way in to the star's surface. Some of the gas in the disk is channeled along the magnetic field lines onto the neutron star's magnetic poles, giving rise to X-ray emission that we see as brief, regular pulses of X-rays as the star spins around once every 10 seconds. Source: *ICRAR Australia & Netherlands Research School for Astronomy*.

New observations reveal inexplicably high magnetic field around a neutron star

International Centre for Radio Astronomy Research (ICRAR), Australia

Astronomers have detected radio jets belonging to a neutron star with a strong magnetic field -- something not predicted by current theory, according to a new study published in *Nature* today.

The team, led by researchers at the University of Amsterdam, observed the object known as Swift J0243.6+6124 using the Karl G. Jansky Very Large Array radio telescope in New Mexico and NASA's Swift space telescope.

"Neutron stars are stellar corpses," said study co-author Associate Professor James Miller-Jones, from Curtin University's node of the International Centre for Radio Astronomy Research (ICRAR).

"They're formed when a massive star runs out of fuel and undergoes a supernova in which the star collapses due to its own gravity. The collapse causes the star's magnetic field to increase in strength to several trillion times that of our own Sun, which then gradually weakens again over hundreds of thousands of years."

University of Amsterdam PhD student Jakob van den Eijnden, who led the research, said neutron stars and black holes are sometimes found in orbit with a nearby "companion" star.

"Gas from the companion star feeds the neutron star or black hole and produces spectacular displays when some of the material is blasted out in powerful jets travelling at close to the speed of light," he said.

Astronomers have known about polar jets for decades but until now, they had only observed jets coming from neutron stars with much weaker magnetic fields. The prevailing belief was that a sufficiently strong magnetic field prevents material getting close enough to a neutron star to form jets.

This *YouTube video animation* shows how the magnetic field lines channel the flow lines of the gas from the donor star's equatorial disc. This *second video here* shows how the donor star's gas ends up being ejected from the neutron star's poles.

Astronomers have known about jets for decades but until now, they had only observed jets coming from neutron stars with much weaker magnetic fields. The prevailing belief was that a sufficiently strong magnetic field prevents material getting close enough to a neutron star to form jets.

"Black holes were considered the undisputed kings of launching powerful jets, even when feeding on just a small amount of material from their companion star," Van den Eijnden said.

"The weak jets belonging to neutron stars only become bright enough to see when the star is consuming gas from its companion at a very high rate.

"The magnetic field of the neutron star we studied is about 10 trillion times stronger than that of our own Sun, so for the first time ever, we have observed a jet coming from a neutron star with a very strong magnetic field.

"The discovery reveals a whole new class of jet-producing sources for us to study," he said.

"Jets play a really important role in returning the huge amounts of gravitational energy extracted by neutron stars and black holes back into the surrounding environment," Associate Professor Miller-Jones said. "Finding jets from a neutron star with a strong magnetic field goes against what we expected, and shows there's still a lot we don't yet know about how jets are produced."

Read the *Nature paper* here (subscription required). This paper is not available in *astro-ph* preprint, but an article by the same authors which describes the physical mechanism of highly magnetised neutron accretion disc behaviour is *available here. Here is the Jansky VLA press release* with details of the VLA observations.

Source: AAAS Eureka Alert 26 Sept 2018. The ICRAR press release is here.

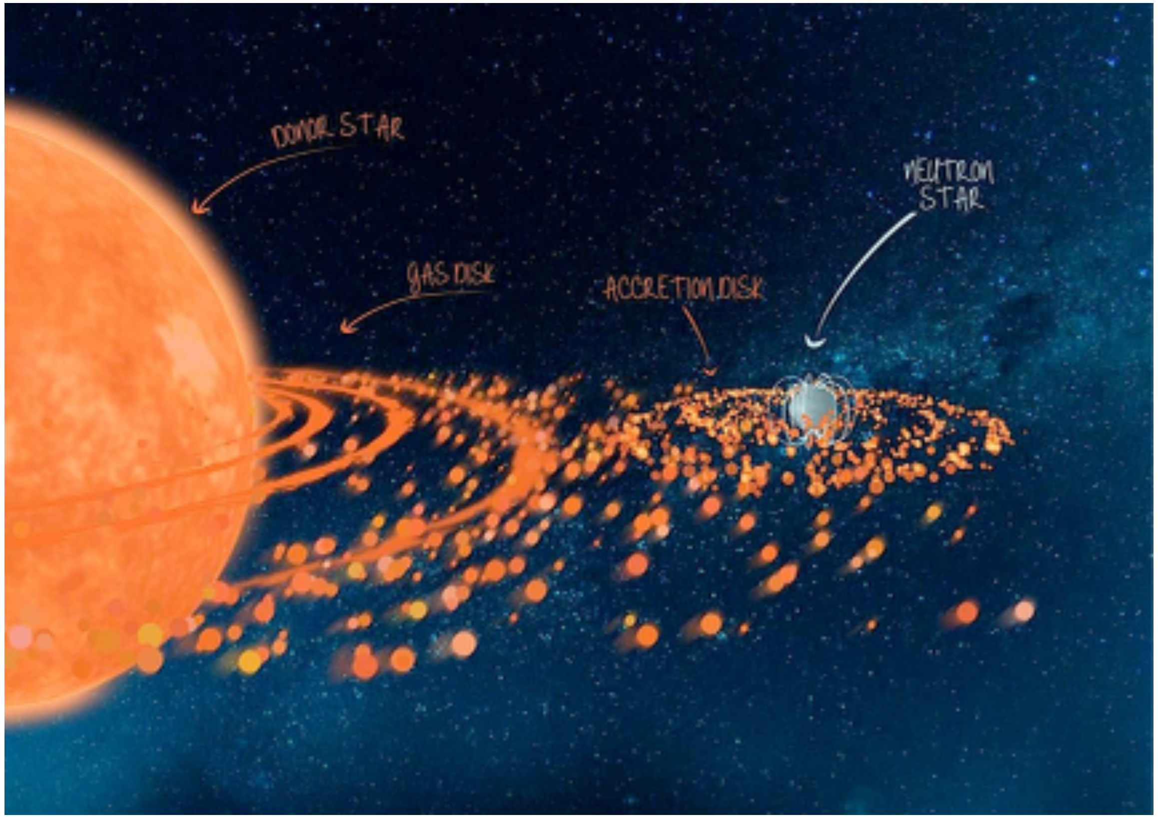


Fig. 1: The binary system Swift J0243.6+6124 consists of a neutron star in a 27-day orbit and a more massive, rapidly rotating donor star. The rapid rotation of the donor star throws off a disk of material around the stellar equator. As the neutron star passes through the disk during its orbit, it picks up some of the outflowing gas, which then spirals in towards the neutron star in an accretion disk. In this binary the neutron star's extreme magnetic field truncates the inward flow. Instead, the gas is redirecting so it descends directly into the star's polar region where it is immediately subsumed into the polar jet and ejected at extreme velocities into deep space. *Source*: *Netherlands Research School for Astronomy. Watch the video animation here.*

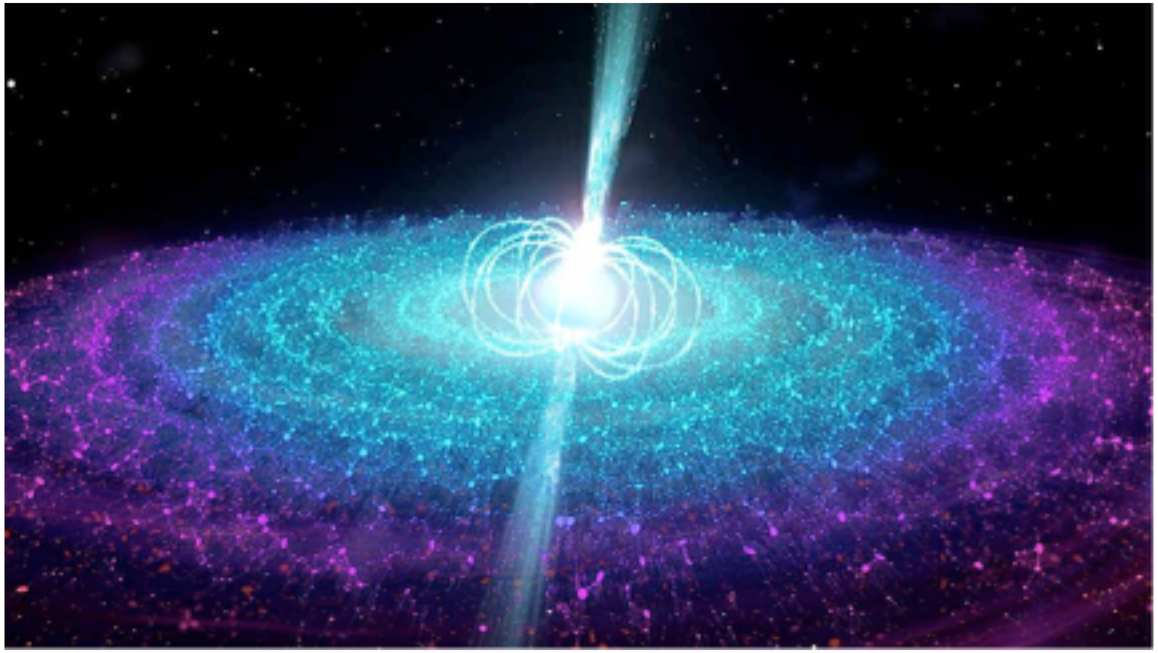


Fig. 2: The strong magnetic field of Swift J0243.6+6124 launches a powerful jet outward from the magnetic polar axis. The neutron star's rotational axis is offset from the binary system's rotational axis. During the bright outburst event in which it was discovered, the neutron star in Swift J0243.6+6124 was accreting at a very high rate, producing copious X-ray emission from the inner parts of the accretion disk. Simultaneous with the Swift satellite observations, the Karl G. Jansky Very Large Array in the USA was studying the same system in the radio bands. By analysing how the radio emission fluctuated with respect to the X-ray emission, the *Eijnden et al. team* deduced that it came from fast-moving, narrowly-focused beams of material known as jets, seen here moving away from the neutron star magnetic poles. *Source*: *ICRAR Australia*. *Watch the video animation here*.

Despite their density, magnetic fields have surprisingly complex electronic circuitry.

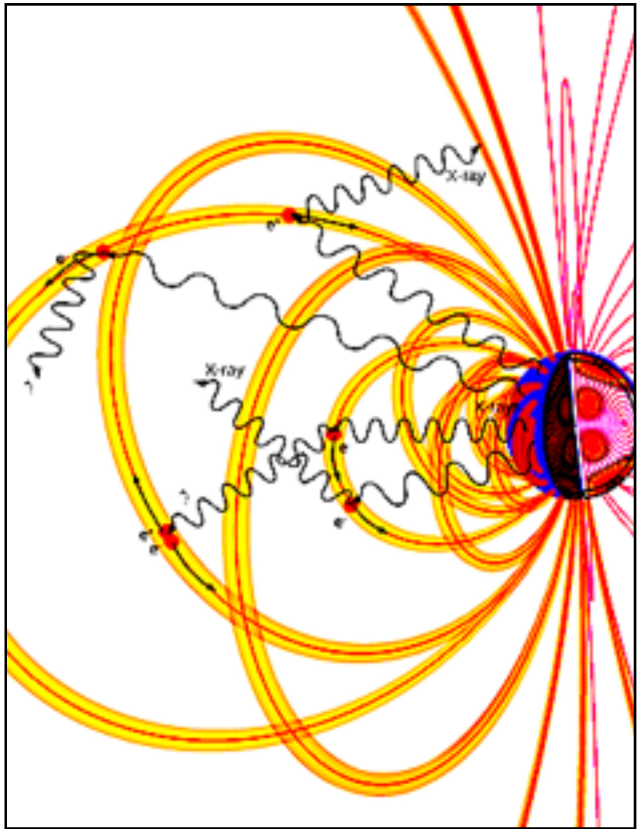
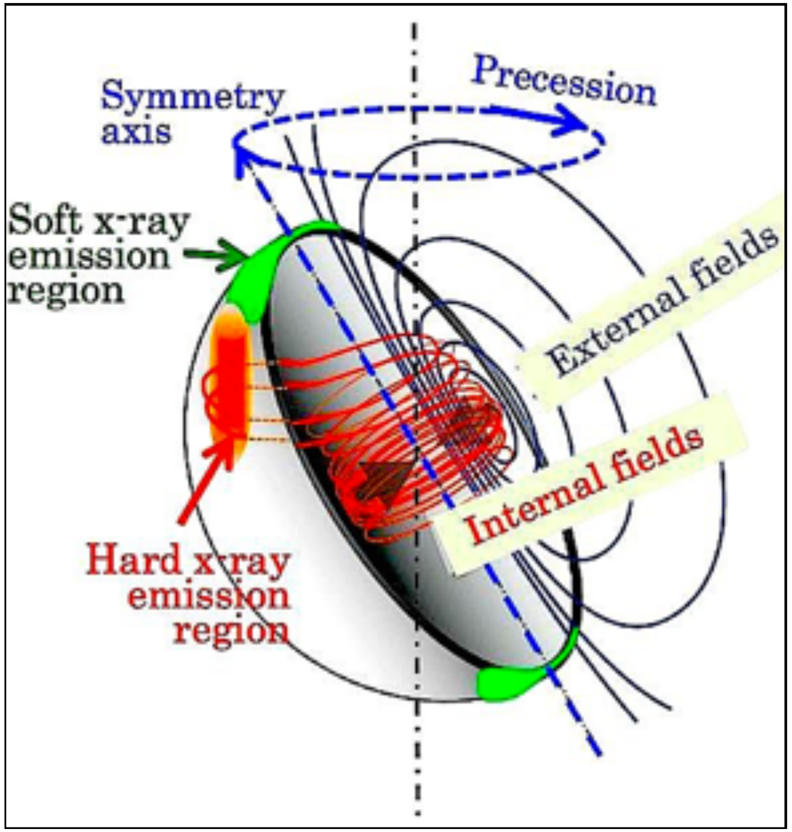
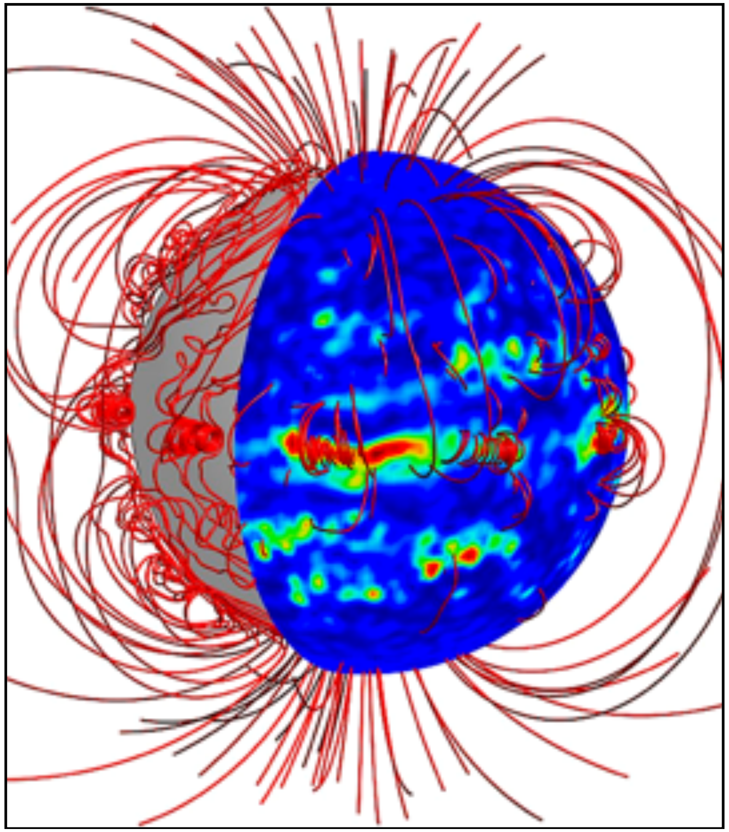


Fig. 3: X-rays from the magnetar 4U 0142+61 are regularly emitted at its rotation period every 8.69 sec, while high-energy hard x-ray pulses are subject to small arrival-time modulations with a period of 15 hours. This suggests that the star is performing free precession or wobbling in its symmetry axis and is very slightly elongated by just 0.01% from the spherical along the axis, creating a lemon shape. *Source*: Makishima et al. 2014: *Wobbling of a magnetar detected with Suzaku*. Physical Review Letters Vol. 112, Issue 17, id.171102.



Fig, 4: 3D magnetic instabilities transfer energy to nonaxisymmetric, kilometre-sized magnetic features, in which the local field strength can greatly exceed that of the global-scale field. These intense small-scale magnetic features induce high-energy x-ray bursts through local crust yielding, Source: Gourgouliatos et al 2015: *Magnetic field evolution in magnetar crusts*. PNAS April 12, 2016 113 (15) 3944-3949.



Fig, 5: Electric currents (yellow), composed mainly of electrons and positrons, flow along the magnetic field lines (magenta). The X-ray emission from the star's surface (black) is scattered resonantly by these charge carriers. The resulting high-energy gamma rays can create further electron-positron pairs. Source: Gabler et al. 2013: *Asteroseismology of magnetars*. MNRAS 430:11 1811-1831. Astro-ph *here*. Non-technical research summary *here*.

Vue de Cap de Bonne Esperance 1719

Vue et Description Du Cap De Bonne Esperance drawn by Henri Chatelain in 1719 (440 mm x 265 mm, 17 1/2 in x 10 1/2 in). This exceptionally fine example of French map-making skills was hand coloured in pink, green, yellow, and blue in this original page of Abraham Chatelain's 1719 striking view of the Cape of Good Hope, with Dutch ships in the harbour and Table Mountain in the background. Separating the two views is an engraved descriptive text which refers mainly to the Company's gardens, 'the most beautiful and curious to be seen in a country that is sterile and frightful.' The lower engraving shows the Dutch fort at the Cape and an observatory established by the Frenchman Tachard and the Jesuit Fathers to observe the southern skies.

The first Europeans to discover the Cape were the Portuguese, with Bartholomeu Dias arriving in 1488 after journeying south along the west coast of Africa. The next recorded European sighting of the Cape was by Vasco da Gama in 1497 while he was searching for a route that would lead directly from Europe to Asia.

Table Mountain was given its name in 1503 by António de Saldanha, a Portuguese admiral and explorer. He called it Taboa da caba ("table of the cape"). The name given to the mountain by the Khoi inhabitants was *Hoeri 'kwaggo* ("sea mountain").

The area fell out of regular contact with Europeans until 1652, when Jan van Riebeeck and other employees of the Dutch Vereenigde Oost-Indische Compagnie (VOC) were sent to the Cape to establish a halfway station to provide fresh water, vegetables, and meat for passing ships travelling to and from Asia. Van Riebeeck's party of three vessels landed at the Cape on 6 April 1652. The group quickly erected shelters and laid out vegetable gardens and orchards, and are preserved in the Company Gardens. Water from the Fresh River, which descended from Table Mountain, was channelled into canals to provide irrigation.

The settlers bartered with the native Khoisan for their sheep and cattle. Forests in Hout Bay and the southern and eastern flanks of Table Mountain provided timber for ships and houses. At this point, the VOC had a monopoly on trade and prohibited any private trade. The Dutch gave their own names to the native inhabitants that they encountered, calling the pastoralists "Hottentots," those that lived on the coast and subsisted on shellfishing," and those who were hunter-gatherers were named "Bushmen."

The first wave of Asian immigration to South Africa started in 1654. These first immigrants were banished to the Cape by the Dutch Batavian High Court. These Asians helped to form the foundation of the Cape Coloured and Cape Malay populations, as well as bringing Islam to the Cape. The first large territorial expansion occurred in 1657, when farms were granted by the VOC to a few servants in an attempt to increase food production.

Map source: Classical Images, Antiquarian Maps, Prints & Books, Melbourne, Australia. info@classicalimages.com

These farms were situated along the Liesbeeck River and the VOC still retained financial control of them. The first slaves were brought to the Cape from Java and Madagascar in the following year to work on the farms. The first of a long series of border conflicts between the inhabitants in the European-controlled area and native inhabitants began in 1658 when settlers clashed with the Khoi, who realised that they were losing territory.

Work on the Castle of Good Hope, the first permanent European fortification in the area, began in 1666. The new castle replaced the previous wooden fort that Van Riebeeck and his men built. Finally completed in 1679, the castle is the oldest building in South Africa.

Simon van der Stel, after whom the town of Stellenbosch is named, arrived in 1679 to replace Van Riebeeck as governor. Van der Stel founded the Cape wine industry by bringing grape vines with him on his ship, an industry which would quickly grow to be important for the region. He also promoted territorial expansion in the Colony.

The first non-Dutch immigrants to the Cape, the Huguenots, arrived in 1688. The Huguenots had fled from anti-Protestant persecution in Catholic France to the Netherlands, where the VOC offered them free passage to the Cape as well as farmland. The Huguenots brought important experience in wine production to the Cape, greatly bolstering the industry, as well as providing strong cultural roots.

By 1754, the population of the settlement on the Cape had reached 5,510 Europeans and 6,729 slaves. But by 1780, France and Great Britain went to war against each other. The Netherlands entered the war on the French side. A small garrison of French troops were sent to the Cape to protect it against the British. These troops, however, left by 1784. By 1795 the Netherlands was invaded by France in Europe, precipitating the VOC's financial ruin. The Prince of Orange fled to England for protection, and established the Dutch Batavian Republic.

Due to the long time it took to send and receive news from Europe, the Cape Commissioner of the time knew only that the French had been taking territory in the Netherlands and that the Dutch could change sides in the war at any moment. British forces arrived at the Cape bearing a letter from the Prince of Orange asking the Commissioner to allow the British troops to protect the Cape from France until the war.

The British informed the Commissioner that the Prince had fled to England. The reaction in the Cape Council was mixed, and eventually the British successfully invaded the Cape in the Battle of Muizenberg. The British immediately announced the beginning of free trade.

Henri Abraham Chatelain was a Huguenot pastor of Parisian origins. He lived consecutively in Paris, St. Martins, London (c. 1710), the Hague (c. 1721) and Amsterdam (c. 1728). Chatelain was a skilled artis, combining a wealth of historical and geographical information with delicate engraving ability and a gift for uncomplicated composition.

Groundbreaking for its time, his work included studies of geography, history, ethnology, heraldry, and cosmography. His maps are a superb example from the golden age of French mapmaking.The publishing firm of Chatelain, Chatelain Frères and Chatelain & Fils is recorded in Amsterdam, from around 1700-1770, with Zacharias living "op den Dam" in 1730.

Henri Abraham Chatelain, his father Zacharie Chatelain (d.1723) and Zacharie Junior (1690-1754), worked as a partnership publishing the *Atlas Historique, Ou Nouvelle Introduction à L'Histoire* under several different Chatelain imprints, depending on the Chatelain family partnerships at the time of publication. The atlas was published in seven volumes between 1705 and 1720, with a second edition appearing in 1732. The volumes I-IV with a Third edition and volume I with a final edition were issued in 1739.

The *Atlas Historique* was one of the most expansive Dutch encyclopaedias of the age. First published in 1705, Chatelain's *Atlas Historique* was part of an immense seven-volume encyclopaedia. Although the main focus of the text was geography, the work also included historical, political, and genealogical information. The text was compiled by Nicholas Gueudeville and Garillon with a supplement by H.P. de Limiers. The maps were engraved by Chatelain, primarily after charts by De L'Isle. The atlas was published in Amsterdam between 1705 and 1721 and was later reissued by Zacharie Chatelain between 1732 and 1739.

Atlas Historique was first published in Amsterdam from 1705 to 1720, the various volumes were updated several times up to 1739 when the fourth edition of Vol. I appeared, declared the "*dernière edition, corrigée & augmentée*."

The first four volumes underwent four printings. The later printings are the most desirable to collectors as they contain the maximum number of corrections and additions. The remaining three final volumes were first issued between 1719-1720 and revised in 1732.

An ambitious and beautifully presented work, the *Atlas Historique* was intended for a readership fascinated by the recently conquered colonies and the new discoveries. Distant countries, such as the Americas, Africa, the Middle East, Mongolia, China, Japan, Indonesia, etc., take an important place in this work.

In addition to the maps, many of which are based on Guillaume De L'Isle, the plates are after the best travel accounts of the period, such as those of Dapper, Chardin, de Bruyn, Le Hay, and others.

Other sections dealt with the history of the European countries. The *Atlas* covers a wide range of subjects including genealogy, history, heraldry, cosmography, topography, chronology, and costumes of the world. All these were illustrated via numerous engraved maps, plates of local inhabitants and heraldic charts of the lineages of the ruling families of the time. The maps, prints and tables required to make up a complete set are listed in detail in each volume. The accompanying text is in French and often is printed in two columns on the page with maps and other illustrations interspersed. Each map and table is numbered consecutively within its volume. All the maps bear the privileges of the States of Holland and West-Friesland.

Recent scholarship in the *Journal of the International Map Collectors' Society* has suggested the compiler of the atlas, who is identified on the title as "Mr. C***" was not Henri Abraham Châtelain, but rather Zacharie Châtelain.

Notes by Doug Bullis

Quivertree under African skies

Sketches of the southern skies made in 1928

The little-known life and sky maps of Anton Pannekoek

Doug Bullis

Anton Pannekoek (aka Panekuk) was a Dutch astronomer, born in 1873 and died in 1960. He studied astronomy and mathematics at Leiden and worked at the Leiden Observatory from 1891 to 1906. In 1921 he founded the Astronomy Institute at the University of Amsterdam, directing it until 1946. He taught astronomy in Amsterdam University from 1925 to 1941.

Pannekoek was doing serious scientific work even as a student. His first monograph was published in 1892 when he was just 19 years old. It dealt with the minima of the variable star Algol. He remained interested in variable stars through much of his life. He also dealt with problems related to accurately calculating the ephemerides of minor planets (i.e., tables giving the calculated positions of an object at regular intervals throughout an orbital cycle). He made maps of the Milky Way and published a work addressing the development of astronomical thought from antiquity to the middle of the 20th century. He founded the study of astrophysics at the University of Amsterdam in 1926, chairing the department from then until 1946.

In 1926 Pannekoek went on an expedition to Java (then a Dutch colony called Batavia) specifically to make a map of the southern Milky Way. His three large-scale drawings are reproduced below.

Pannekoek received several awards for his writings on the structure of the Milky Way, astrophysics, and astronomical history, most notably the gold medal of the English Royal Astronomical Society in 1951. There is a Panekuk Crater on the moon and a minor planet designated 2378 Pannekoek.

Pannekoek's bibliography

- *Minima von Algol am 2 und 5. Nov. 1891*, Astronomische Nachrichten, **130** , 435, 1892.
- *Ephemeride des Planeten (329) Svea für die III Opposition*, A-R, **137**, 15, 1894.
- *New Charts for inserting the Milky Way*, Journal of the British Astronomical Association, **8** , 80, 1897.
- *Einige Bemerkungen zur »jährlichen Refraction«*, Astronomische Nachrichten, **167,** 389, 1905.
- *The relation between the spectra and the colors of the stars*, idem, **9** , 292, 1906
- *Researches into the structure of the galaxy*, Koninklijke Nederlandsche Akademie van Wetenschappen Proceedings, **13** , 239, 1910.
- *A photographic method of research into the structure of the galaxy*, idem, **14** , 579, 1911.
- *On the origin of the coronal spectrum*, Bulletin of the Astronomical Institutes of the Netherlands, **1** , 127, 1922.
- *tudies on line intensities in stellar spectra.* **2** ,223, 1925.
- *On the possible existence of large attracting masses in the center of the galactic system*, Bulletin of the Astronomical Institutes of the Netherlands, **4** , 39, 1926.
- *The luminosity of stars of different types of spectrum*, Koninklijke Nederlandsche Akademie van Wetenschappen Proceedings, 9, 134, 1926.
- *Results of observations of the total solar eclipse of June 29, 1927. I Photometry of the flash spectrum*, Koninklijke Akademie van Wetenschappen te Amsterdam, XIII. 5, p. 1-106, 1928.
- *Bosscha-Sterrenwacht*, vol. 2, 1, Amsterdam, Druk de Bussy, p. A3-A73, with 6 star charts, 1928.
- *Theoretical intensities of absorption lines in stellar spectra*, Publications of the Astronomical Institute of the University of Amsterdam, **4** , 4, 1935.
- *Fluorescence phenomena and central intensities in Fraunhofer lines*, Monthly Notices of the Royal Astronomical Society, **95** , 725, 1935.
- *The hydrogen lines near the Balmer limit*, MNRAS, **98** , 694, 1938.
- *The Stellar Temperature Scale*, Astrophysical Journal, **84** , 481, 1936.
- *Surface gravity in supergiant stars*, Bulletin of the Astronomical Institute of the Netherlands, **8** , 175, 1937.
- *Line intensities in the spectra of advanced type*, Publications of the Dominion Observatory Ottawa, 8, 141, 1946.

ANNALEN V/D BOSSCHA-STERRENWACHT

LEMBANG (JAVA)

VOL. II. 1ste Gedeelte

A. PANNEKOEK

DIE SÜDLICHE MILCHSTRASSE

ausläuft, nach u. nach ε — ζ — δ Vol abnimmt, und sich nach r. bis *B* Car ausdehnt. Von dem Licht χ Car — α Pic wird er durch eine Dunkelheit zwischen *B* Car und α Pic getrennt. Auch zwischen ε Car und β Vol, etwas nach α Vol hin, ist es vielleicht ein wenig dunkler.

22. Zwischen υ und θ Car entströmt dem Lichtband *l* — φ Car ein breiter, schwacher Lichtstrom, mit einer Dreieckspitze nach ω Car; von dort geht er weiter nach l. nach α — λ Mus. Nach unten zu breitet sich von ihm ein ganz schwaches Licht nach α — γ — δ Cham aus, das von dem Schein in Volans durch einen Streifen getrennt wird, der l. an β Car entlang nach unten geht. Das Lichtband υ — ω Car — α — λ Mus umschliesst einen dunkleren Raum, von dem die dunkle Bucht λ Cen — *z* Car einen Teil bildet. Ein schwacher Lichtstreifen λ Cen — θ Car zerteilt ihn; über diesem liegt ein dunkler Streifen, von θ ½ *z* Car in der Richtung nach δ ε Cru, der oberhalb von λ Cen mündet, dort λ ¼ 65 Cen in das Licht eindringt und einen Seitenast l. an *z* Car entlang nach o. schickt. Unterhalb des Lichtstreifens liegt ein dunkles Band oder eine Reihe dunkler Stellen, die unterhalb λ Cen, auf λ Mus ⅓ θ Car und s.ö. von θ Car angegeben wurden.

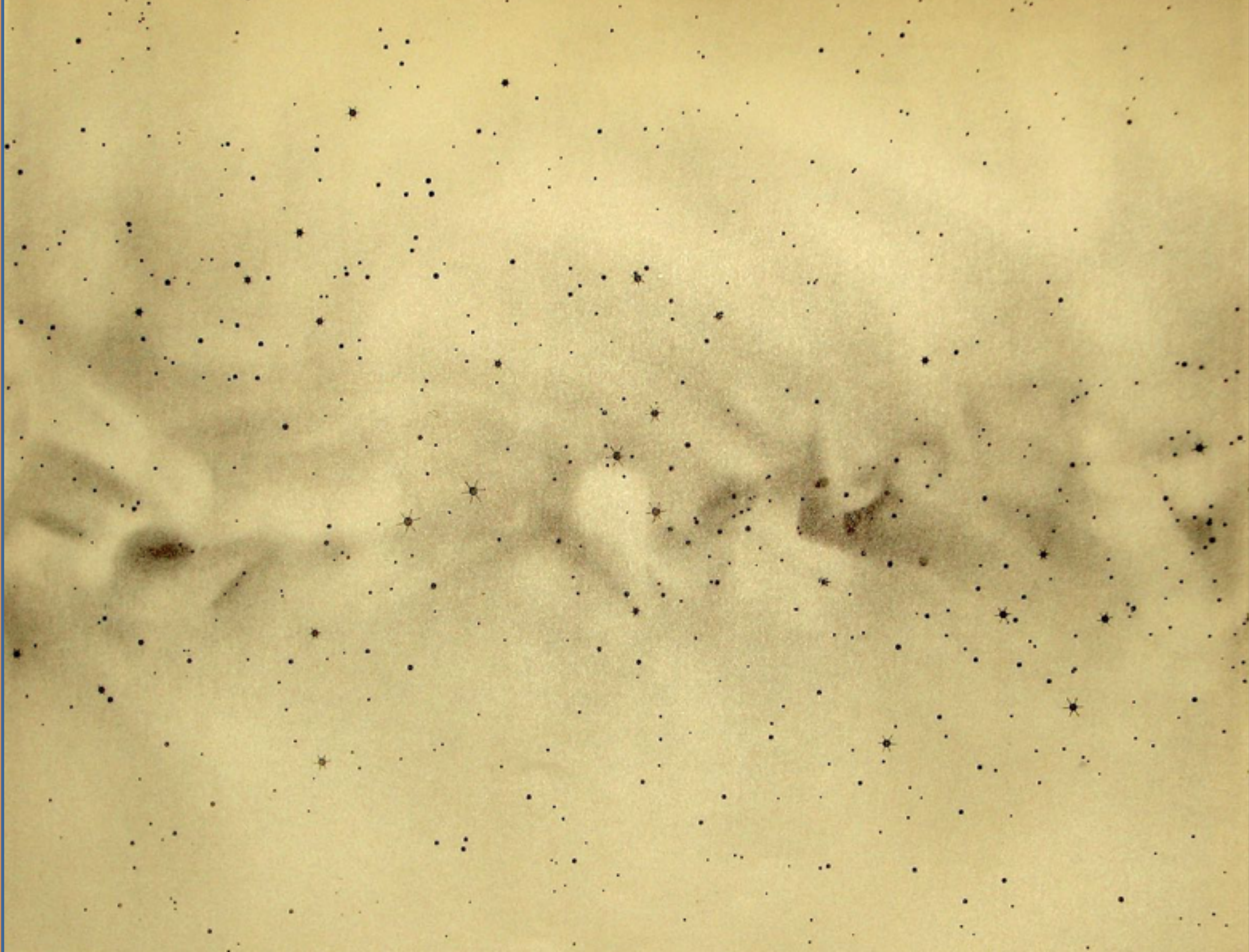
Zwischen α β und γ δ Mus liegt ein dunkler Fleck; nach r. u. verläuft er als Streifen, der halbwegs *K* Car nach s. umbiegt; l. o. setzt er sich schwach fort und bildet einen dunklen Flecken η Mus 1/8 α Cir, der das helle F Licht begrenzt. Ein schwacher Lichtstreifen geht über γ δ Mus, der sich verbreiternd die Richtung α Cir einschlägt und darauf noch breiter werdend sich nach γ TrA hin ausdehnt. Von γ δ Mus geht ein sehr schwacher Schein streifenförmig nach α Aps; r. davon liegt ein dunkler Raum nach γ — δ Cham hin. Ein dunkler Raum befindet sich γ TrA ⅓ δ Mus; u. ihm zeigt sich ein sehr schwaches, breites Band von γ — α TrA nach r. u. nach β — γ — α Aps, vielleicht noch bis γ — δ Cham erkennbar.

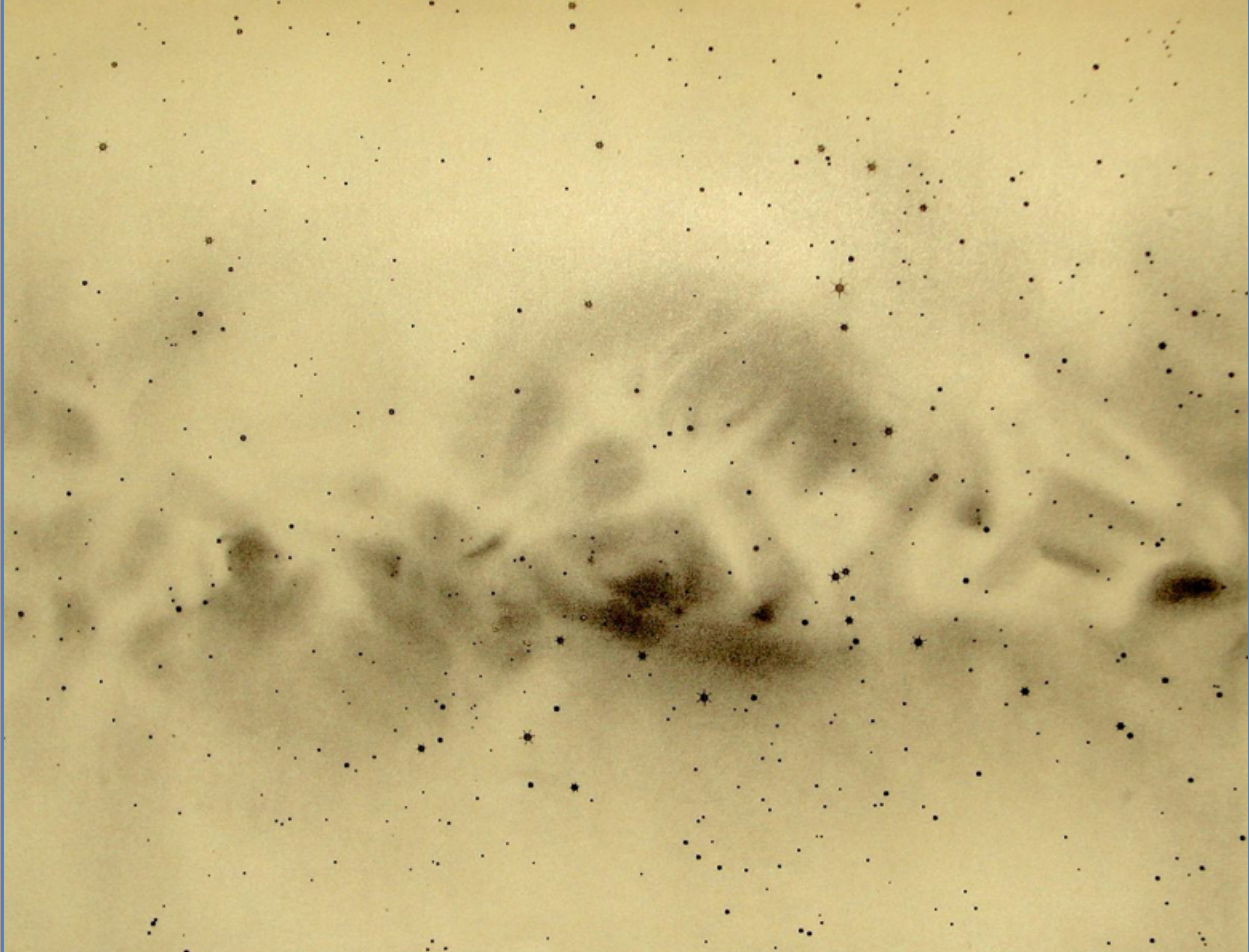
23. Von dem hellen Lichtflecken F geht der Lichtstrom, zuerst abnehmend, östlich nach α Cen und α Cir. Ein ununterbrochener Lichtstreifen geht von F gerade nach α Cir und unten an ihm entlang, und setzt sich schwächer fort nach β TrA. Nach u. breitet das Licht sich schwächer aus nach α und γ TrA; hier wird es vielleicht wieder etwas heller. In der Mitte schliesst sich das schwache von δ Mus kommende Lichtband an (22).

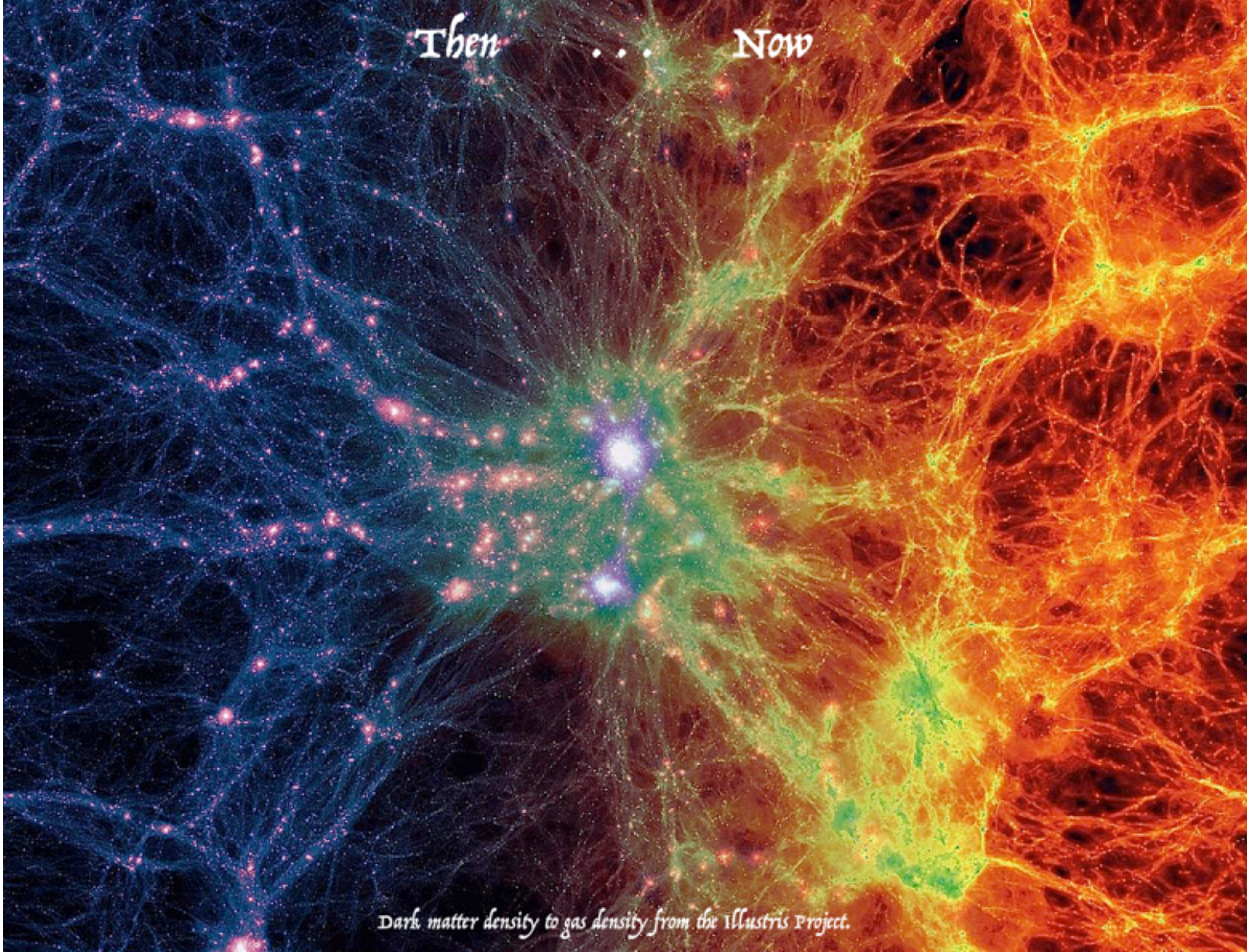
Der Lichtstreifen *m* Cen — α Cir wird von den höherliegenden Teilen des Lichtstroms durch eine Reihe dunkler Flecken getrennt, die zusammen oft wie ein dunkler Streifen α Cir — *J* Cen aussehen; der deutlichste liegt β ½ *m* Cen, unregelmässig gebogen, in verschiedener Form beschrieben; andere sind angegeben *J* ⅓ *m* Cen, α Cir ⅓ β Cen, und ein Streifen auf der Linie *J* Cen — α Cir. Ihre Fortsetzung finden sie in einer Gruppe viel auffal-

U.A. 22. In der U.A. geht die untere Grenze des Lichtes über *G* Car, γ Cha, β und α Aps, und 3° s. an α Tr A entlang. Um γ δ Mus herum ist das Licht etwas heller; zwischen γ δ und α β Mus ist ein schwach dunkler Streifen, der nach r. in das Randlicht mündet, nach l. oberhalb von δ Mus aufhört. Ein schwacher halbkreisförmiger Lichtbogen konvex nach s. geht von γ nach α Tr A; zwischen diesen Sternen ist es dunkler.

U.A. 23. In der U.A. wird das Licht l. vom Kohlensack im weiteren Verlauf nach l. nach Circinus und β Cen, allmählich schwächer. Die u. Grenze des hellen Lichtes ist ein Bogen η Mus, η Mus 1/3 α Cir, γ Tr A. In dem gleichmässigen Strom liegt ein hellerer Streifen u. an β und α Cen entlang, der über γ δ Cir weitergeht und sich dann bis ι Nor ⅓ η Ara und ι Nor ⅓ ζ Lup verbreitert. Ein abgerundet-dreieckiger schwarzer Fleck befindet sich zwischen θ — ε — δ Cir. Nach u. liegt ein gleichmässiges Licht bis γ und β Tr A; ein dünner Lichtstreifen geht über γ Tr A nach δ und ist noch bis η Ara zu verfolgen. Der schwache Bogen γ — α Tr A ist noch weiter bis δ Tr A zu erkennen.







Dark matter density to gas density from the Illustris Project.


Astronomicum Cæsareum:

Our earliest ancestors, from deep prehistory, gazed up at the sky in awe. We soon determined through repeated observations that the celestial bodies appear to follow prescribed paths and that their positions in the sky coincided with or produced effects on earth. For the Egyptians, Isis' tears over the death of Osiris made the Nile rivers swell but this annual flooding could be predicted with considerable precision based on the heliacal rising of the sky's brightest star, Sirius. Moreover, the sun determined days and nights and years and seasons and regulated the plantings and harvests of agricultural civilisation. If the sun, for most of history considered a planet, had such profound effects on the earth and its inhabitants, then it followed, quite reasonably, that the other wandering stars or planets produced similar effects too.

Aristotle's Crystalline Spheres

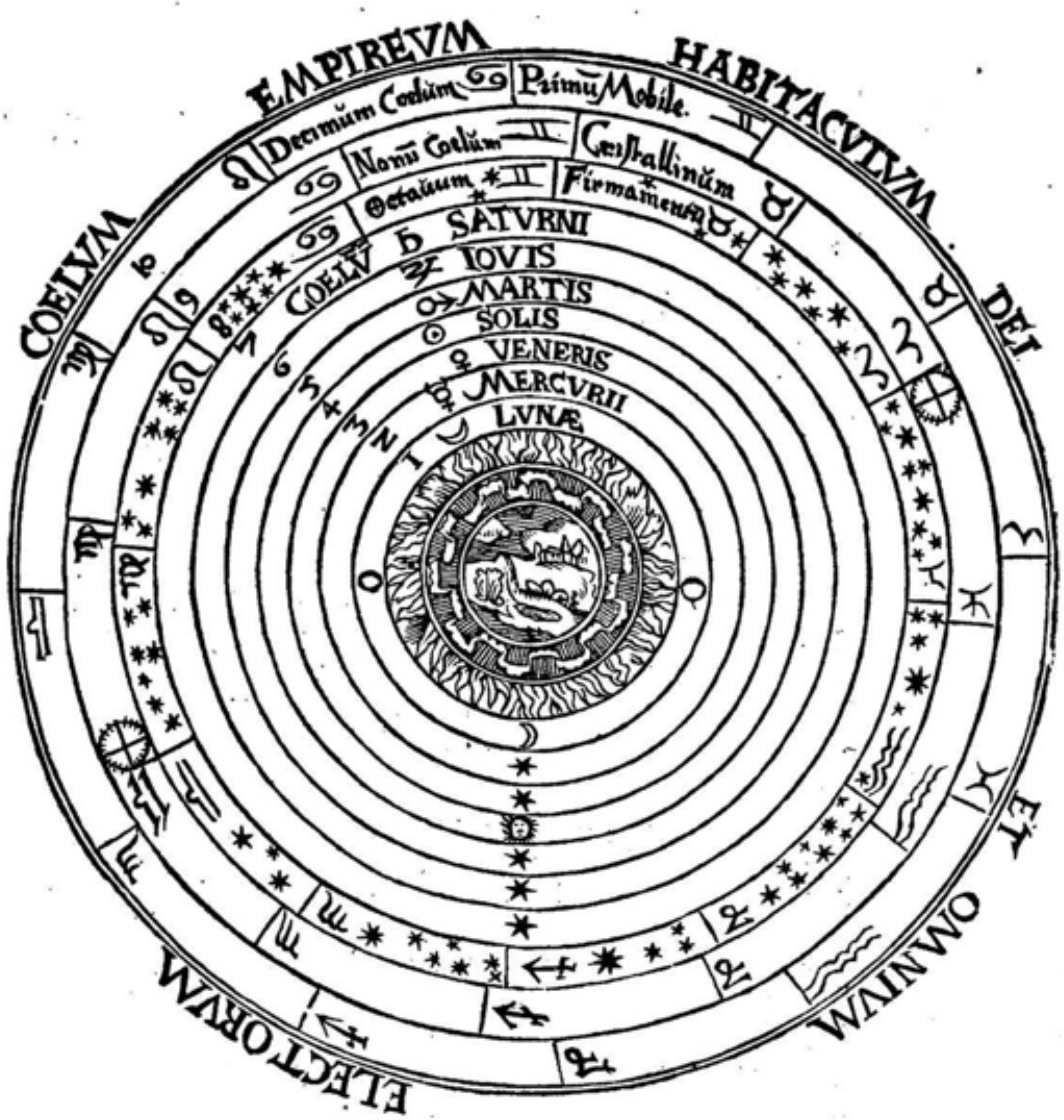
The universe as conceived by Aristotle (384–322 BC) comprised concentric, nested crystalline spheres – a beautiful concept but profoundly flawed as it could not account for the retrograde motion of the planets and variations in their apparent brightness. The solution was proposed by, among others, the founder of trigonometry, Hipparchus (c.190–120 BC), and formalised by the great mathematician and astronomer, Ptolemy (c.100–c.170 AD) in Alexandria, Egypt. The Ptolemaic system retained Aristotle's concentric spheres and comprised a stationary Earth at the centre, encompassed by the spheres of Moon (☽), Mercury (☿), Venus (♀), Sun (☉), Mars (♂), Jupiter (♃), Saturn (♄), the fixed stars or firmament comprising the twelve signs of the zodiac, and beyond that a tenth (sometimes the ninth) sphere, the Aristotelian Primum Mobile that imparts motion to all the other spheres, and beyond that, the *coelum empireum habitaculum dei omnium electorum*, the dwelling place of God and the elect. This system, but for minor revisions was accepted for 1400 years.

Astronomicum Caesareum

It is not at all surprising that ancient observers assumed an immobile earth at the centre of the cosmos. The night sky, as it passes overhead traces a sphere and like us, the ancients did not feel the earth moving underfoot; rather, it appeared that the heavens revolved about them. To Aristotle and most of his contemporaries, it was incomprehensible that the earth should move. According to Ptolemy, if the earth moved or rotated then it risked 'falling out of the heavens.' But for earth to remain immobile and central in the cosmos demanded the construction of a complex geometrical system of epicycles, deferents and equants, their ratios and positions determined arbitrarily to correspond with observation. It is claimed that the Spanish monarch, Alfonso X of Castile (1221–84) remarked, "had I been present at the Creation, I would have given some useful hints for the better ordering of the universe."

> "No man is so utterly dull and obtuse, with head so bent on Earth, as never to lift himself up and rise with all his soul to the contemplation of the starry heavens."
> =Seneca, *Physical Science in the Time of Nero*, Book VII Chapter I, p. 271.

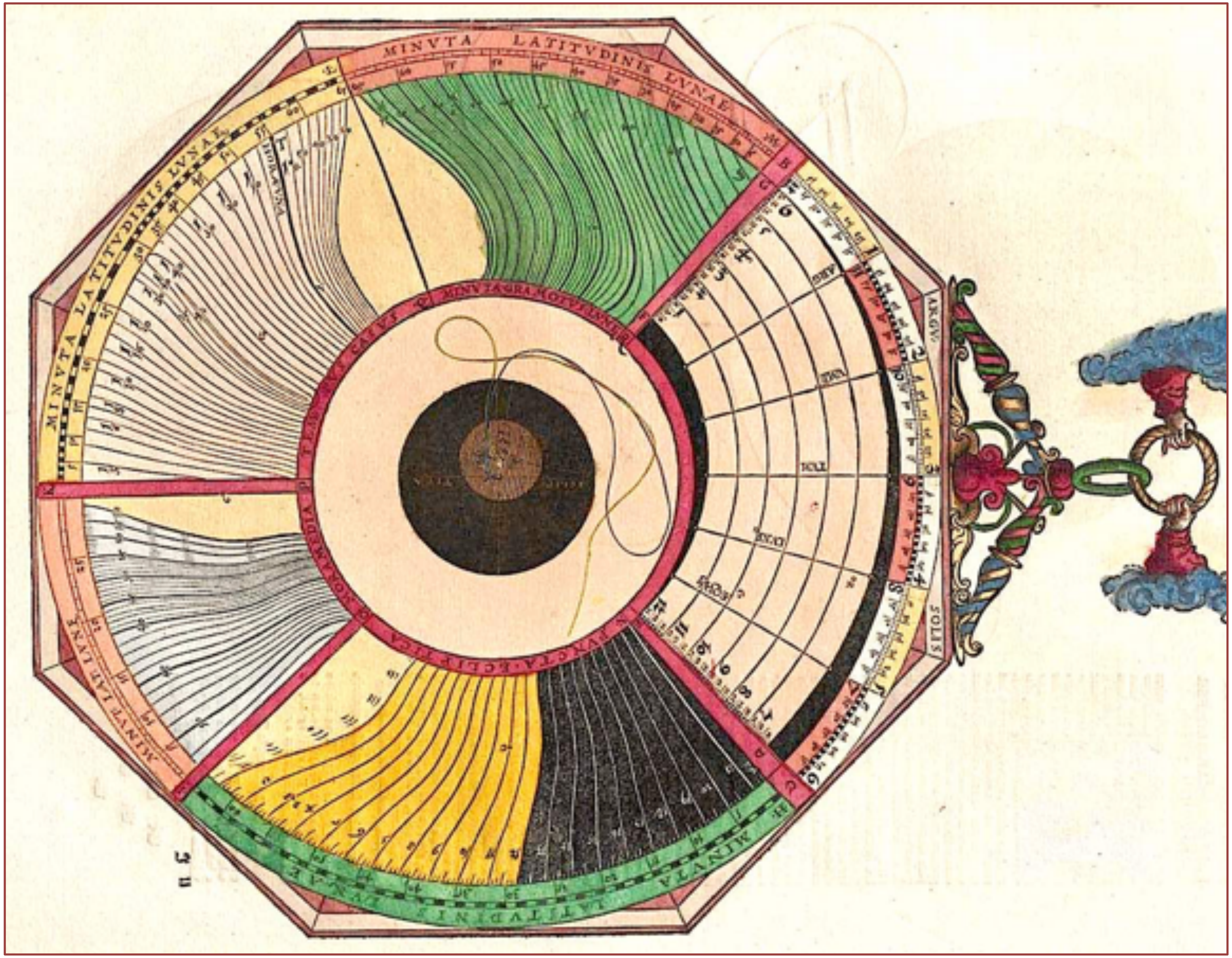
Peter Apian (1495–1552), the son of a shoemaker, was a German mathematician and astronomer. He studied at the University of Vienna where he studied mathematics, astronomy and astrology. Emperor Charles V awarded him with printing privileges, a knighthood, and appointed him his court mathematician. Apian's Astronomicum Caesareum is dedicated to the Emperor, with every page worthy of such an illustrious patron. The splendid dragon volvelles, one of which is reproduced below, were used to predict lunar eclipses, with the head and tail of the dragon depicting the lunar nodes, or the two times that the moon crosses the ecliptic – especially important as lunar eclipses only occur within close proximity to these lunar nodes.



Woodcut from Peter Apian's *Cosmographia*, illustrating the Ptolemaic, earth-centred cosmos. Printed in Antwerp by Gillis Coppens van Diest & Arnold Birckmann, 1540.

According to this, the Earth is centred within an ocean of waves, inside a circle of solar fire, inside the moon, inside Mercury–etc.etc.– out to Saturn, which is located inside the *Octalium Firmamentum* or the 12 zodiacal signs, which in turn is located inside the *Nonu Coelum* (Ninth Heaven), which lies inside the *Decimum Coelum Primu Mobile* (Tenth Heaven of the Prime Mover), which lies inside the ultimately boundless Heavenly Empire of All the Elect.

Gentlemen, I'm afraid it's turtles all the way up.



Peter Apian's *Astronomicum Caesareum* (Astronomy of the Caesars) was a lavishly illustrated, large folio volume published in 1540. Apian predated the desktop publishing movement by 450 years, being both author and printer of his book. It is regarded by many as the most typographically impressive scientific manual of the sixteenth century. Owen Gingerich claimed it was "the most spectacular contribution of the book-maker's art to sixteenth-century science."

This magnificent book is beautifully illustrated with remarkably complex and detailed woodcuts, usually attributed to Michael Ostendorfer, including numerous woodcut initials and more than twenty *volvelles*, some with as many as six paper discs rotating on different axes.

Volvelles served several purposes: astronomical, astrological, mathematical, and even medical. *Volvelles*, from the Latin *volvere*, to turn, was first introduced into printed books by the very first astronomer-printer, Regiomontanus (1436–76), although they appear in manuscript books from the thirteenth century. They idea may have originated with Arab astronomers in the golden age of Islamic science from the 8th to 12th centuries.

Volvelle for calculating duration and size of lunar eclipses, from Apian's *Astronomicum Caesareum*, 1540. Image courtesy of Bayerische Staatsbibliothek. 36.6 × 51.5cm

Another impressive and rather complex looking *volvelle* is used to calculate the size and duration of lunar eclipses. Apian describes the use of this particular *volvelle* with reference to two example eclipse calculations: the first, a partial lunar eclipse on Emperor Charles V's birthday, 5 November 1500; the second is the partial lunar eclipse of October 15, 1502, on the birthday of King Ferdinand I, brother to Charles V. This *volvelle* has no moving parts besides two strings attached at the center, that originally would have been threaded with small beads that functioned as sliding markers to transfer radial distances.

The *Astronomicum Caesareum* is a compendium of current astronomical knowledge, although it does include the new notion (at least in the West) that the tails of comets point away from the sun. Also included are observations for five comets, including Halley's in 1531. In a historical first, Apian recommended the use of coloured or dark glasses to observe eclipses of the sun.

Apian was instrumental in popularising paper instruments. They appeared with increasing frequency throughout the sixteenth and seventeenth centuries. They became so popular that the makers of traditional scientific instruments sought to prohibit the sale of these "paper frauds", claiming they were "a mere deception through which the buyer is cheated." (From a Nuremberg Statute of 1608.)

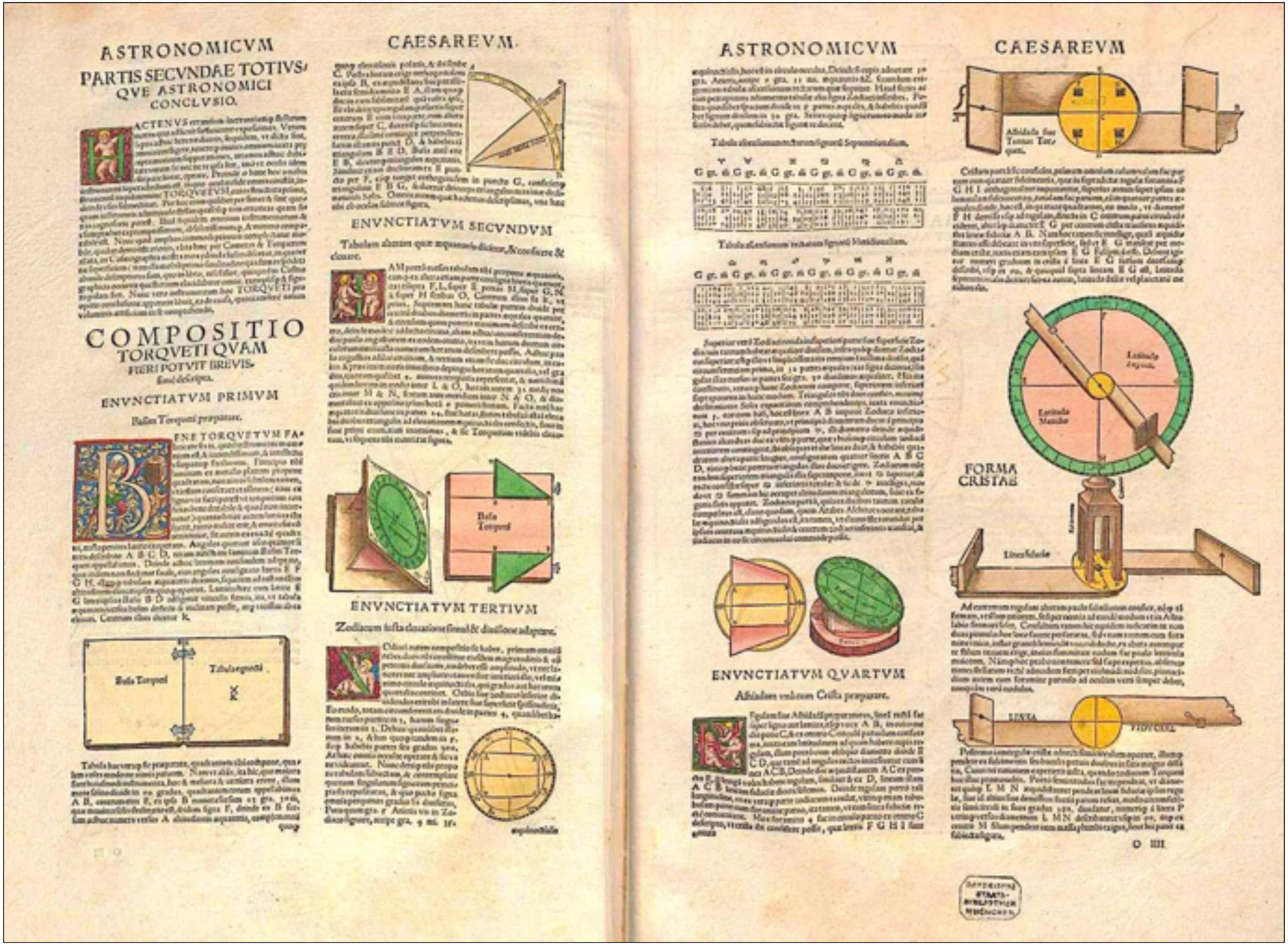
Fanciful rendering of the 27 cardinal points which were thought to indicate the length and duration of lunar eclipses.

One might assume that the book's publication, just three years before Copernicus' *De revolutionibus orbium coelestium*, was rather inopportune and that Apian's didactic masterpiece would have been rendered immediately obsolete. However, it continued to be used for its relative ease of use as a manual, and because Copernicus' heliocentric model was no more accurate at predicting planetary motions than the Ptolemaic geocentric system expounded in *Astronomicum Caesareum*.

Much greater accuracy was achieved only from the beginning of the subsequent century with Johannes Kepler's laws of planetary motion that elegantly reimagined Ptolemy's circular orbits and uniform motion with elliptical orbits and planets that moved faster, the closer they approached the sun.

Ioannes Kepler called Apian's *Astronomicum Caesareum* "a waste of time and ingenuity".* But Apian's work was not intended for mathematical astronomers like Kepler. Apian made clear in his preface that his tome was for the layperson. It was intended to make astronomy more accessible to a broader audience. In that, Apian succeeded — and while he was at it he produced an enduringly magnificent book about the art of typographic in his time.

* John North, *Cosmos: An Illustrated History of Astronomy & Cosmology*, p. 262.



The ATM movement started with a stick in the ground. The first astronomical instrument was most likely a simple gnomon, a vertical stick taller than the observer, by which the observer could roughly determine an objects elevation above the horizon. Gnomon's were 2-dimensional because it measured only approximate declination. There was no azimuthal measure since the R.A. axis was wherever one stood.

This two-page spread appeared towards the end of Apian's book. It is effectively a how-to manual for constructing astronomical instruments.

ladies who launched

PART ONE IN NIGHTFALL'S SERIES ABOUT THE "HARVARD COMPUTERS"

Science benefited enormously from the contributions of Henrietta Swan Leavitt, Williamina Fleming, Antonia Maury, the marvellously named Annie Jump Cannon, and in the following generation, Cecilia Payne. These women detected, classified and cataloged several hundred thousand stars. They found unsuspected relationships that became crucial discoveries about our universe.

I - Henrietta Swan Leavitt

From rejected to respected, one scribble at a time

Douglas Bullis

A century and a half ago, Henrietta Swan Leavitt (1868-1921) of the Harvard College Observatory was tediously comparing variable stars' brightnesses to the time period over which they varied. She noticed an odd pattern and made drawings of it. The light curve she discovered was one of the most notable in the history of astrophysics.

In 1912 astronomers knew how bright the stars seemed, their magnitude as seen visually, but they had little idea how bright they actually were, their *intrinsic luminosity*. At the time Leavitt was cataloging Cepheid variables in the Small Magellanic Cloud. She listed 25 in order of period. She was curious to find that their brightness was directly related to their period. By comparing a Cepheid's *apparent magnitude* with its *absolute magnitude* it was straightforward algebra to calculate the star's distance. This in turn gave the distance of the galaxy in which it is located.

Accurate distancing was a crucial advance to understanding of the size and evolution of the Universe. Leavitt's discovery enabled astronomers to estimate the distances of stars in faraway galaxies just as accurately as in our own Milky Way.

Leavitt died in 1921. Two years later Edwin Hubble, working at California's Mount Wilson Observatory, serendipitously discovered a Cepheid variable in the Andromeda Galaxy using the observatory's 100-inch reflecting telescope. Using Henrietta Leavitt's light curve calculations, Hubble eventually determined that the star's period and absolute magnitude and in 1929 announced that the galaxy was 900,000 light-years away. This immediately enlarged the universe by an astonishing amount.

Some years later Walter Baade discovered that there were two types of Cepheid variable stars. Hubble was comparing a more luminous Type II Cepheid in Andromeda with a dimmer Type I Cepheid in our own galaxy. Baade's calculations showed that the Andromeda Galaxy was actually some 2 million light-years away. With that the size of the known universe doubled yet again. Baade announced this finding to the amazed astronomers at the 1952 meeting of the International Astronomical Union in Rome.

Decades later in the 1990s, Adam Riess and his team of astronomers refined Hubble's distance-velocity law to show that the expansion is actually accelerating – for which they were awarded the Nobel Prize in Physics.

Riess had used Leavitt's light curves when he was still a graduate student doing cosmology research at Harvard Centre for Astrophysics (CfA). A mere two years after graduating he lead-authored the paper reporting the discovery of the Universe's accelerating expansion.

None of this would likely have transpired without Leavitt's discovering the period-luminosity relationship, Leavitt's Law remains to this day one of our most reliable tools for studying distance relationships the Universe.

Leavitt's legacy continues. For example, a Hubble Space Telescope result announced in January 2018 highlights the use of her relationship – now generally called Leavitt's Law – in ongoing attempts to identify whether new physics has been uncovered in recent cosmology observations.

As with many other female scientists of her time, Leavitt's contributions to her field went largely unacknowledged by the scientific peers. An article about her on the American Association of Variable Star Observers website reports: "As she had lived quietly, unnoticed, so her death left barely a ripple among her peers." She was so dimly perceived that in 1925, when the Swedish mathematician Gösta Mittag-Leffler wrote her, "Honoured Miss Leavitt, your admirable discovery ... has impressed me so deeply that I feel inclined to nominate you to the Nobel Prize in Physics for 1926." He was dismayed to learn she had died four years earlier.

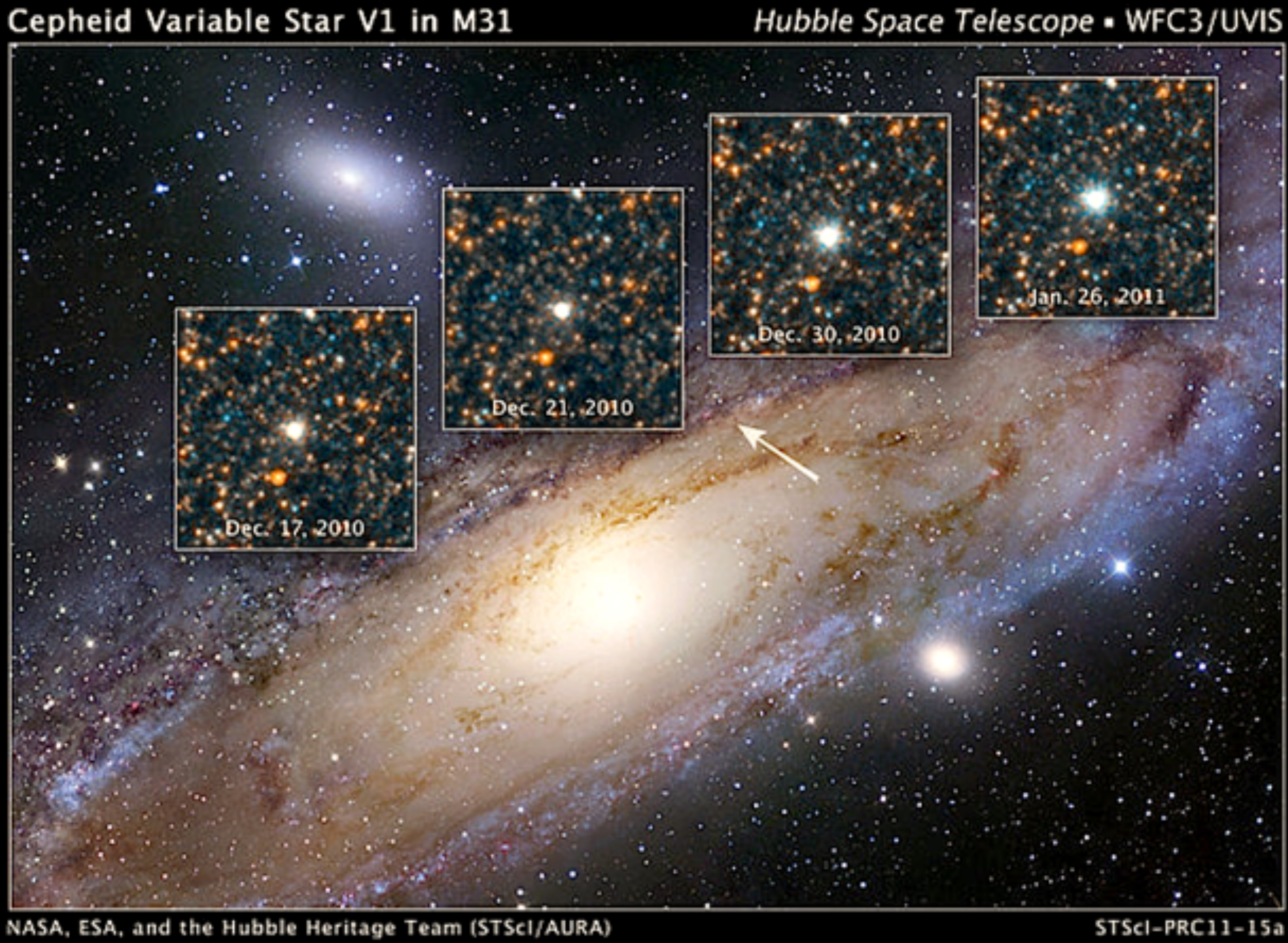


Fig. 1: There is a close relationship between the period and intrinsic brightness of a Cepheid variable star. The longer the period, the greater the star's luminosity. The relationship between a Cepheid's pulsation rate and the brightness of its observed luminosity enables astronomers to use these stars as celestial yardsticks to measure stellar distances, even if the star in question is located in a distant galaxy. An astronomer need only determine a Cepheid's period and apparent magnitude, then calculate its distance. The calculation gives the star's absolute magnitude — how bright that star would appear if it were placed at a standard distance of 32.5 light-years.

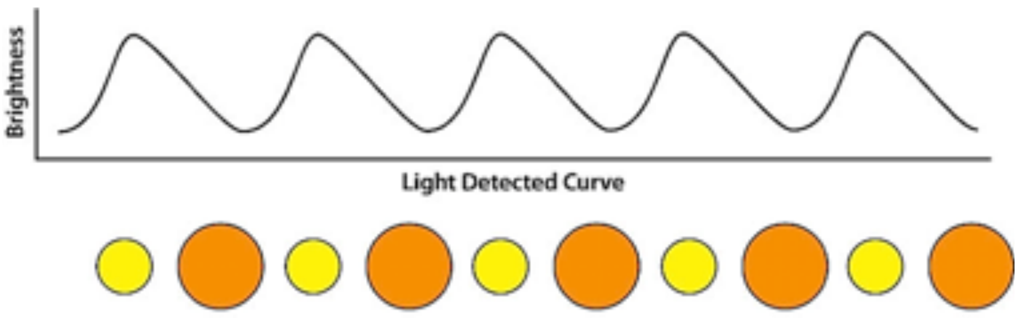


Fig. 2: In 1908 while cataloging variable stars in the Small Magellanic Cloud, Leavitt noticed that the brighter Cepheid variables had longer periods than the dimmer Cepheids. When she plotted the apparent brightness of those variables against their periods she obtained a variation cycle like the above. The implication was clear: since the Magellanic stars are all at approximately the same distance, the Cepheid variables that appeared brighter in the sky were in fact intrinsically brighter. When she plotted the apparent brightness of the Cepheids against their periods she obtained a variation cycle like the above.

She published her results in 1912 to a resounding yawn. Few astronomers perceived the potential of her period-luminosity law. Her mentor Edward Pickering was a notable exception. He heartily congratulated Leavitt and encouraged her to document more Cepheids. She could detect their variations readily in the Milky Way, faintly in the Magellanic Clouds, but no further. Photographic plates of the time weren't sensitive enough to reveal the Cepheids' subtle magnitude differentials in more distant galaxies.

Neither she or anyone else understood why the stars varied in the first place. Only long after she died did astronomers determine that stellar variability was due to the stars pulsating in size. When a star expands in size its surface area increases in inverse proportion to the drop in its surface temperature. Since the luminosity of a star varies to the square of its radius (R^2) while its surface temperatures varies to the 4th power (T^4), when a Cepheid becomes hotter inside it swells in size and its brightness decreases.

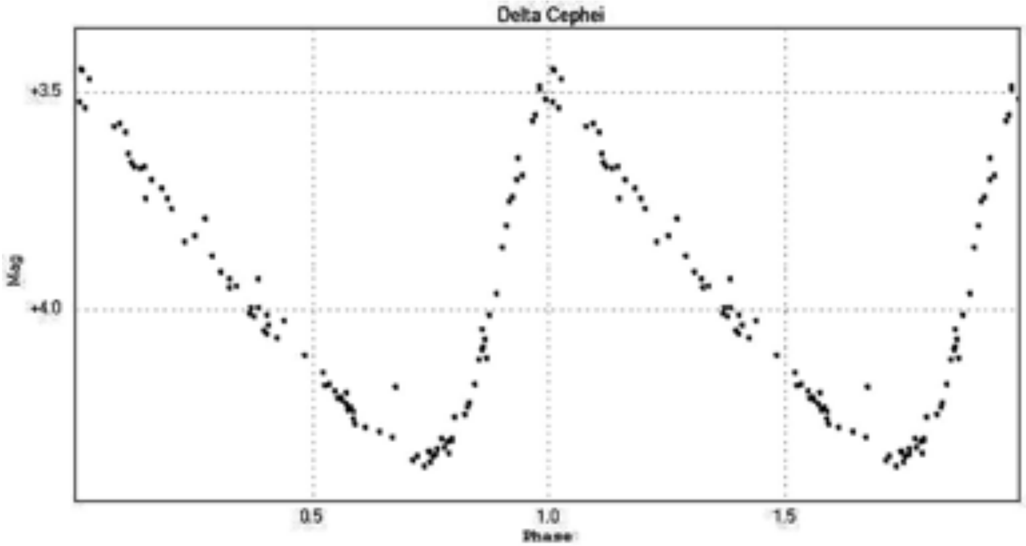


Fig. 3: Leavitt's discovery was a crucial observation. By measuring the amount of time it took a Cepheid variable to complete a cycle it was possible to obtain its intrinsic brightness or luminosity. Since Cepheid variables are by nature very bright stars, the advent of photography made it easy to spot them in nearby galaxies. Above, a Cepheid with a 30-day period is shown to be about 10,000 times brighter than the Sun, meaning it can be seen up to 100 times further away. Given the photographic sensitivities of the time, such long arms could reach out to embrace the Local Group galaxies.

Nearby stars proved trickier to estimate correctly. Leavitt knew how to use the parallax method to calculate a star's distance, but no local Cepheids were close enough for the parallax method to work. Leavitt turned shortcoming into advantage by a non-intuitive workaround. She used parallax to calculate the distances of stars close to the Sun. She then calculated the motion of the Sun relative to the nearby Galactic field stars. She then juxtaposed local motions against the apparent drift of Cepheid variables as seen against the background of very distant stars. The differential gave her the distance to a small but useable number of relatively nearby Cepheid variables. Applying her law of apparent brightness versus period, she could calculate the distance to the Small Magellanic Cloud (today known to be 190,000 light years).

De-mything the Harvard Harem

Between 1880 and 1919 a small group of women working in a cramped office at Harvard Observatory elevated the onerous duty of cataloguing page after page of stars and “faint fuzzies” into science-changing discoveries.

Object catalogs are one of astronomy’s greatest contributions to the science of physics. In effect, catalogues are an all-sky close-up view of a specific object type. Well-designed catalogues are at the centre of most major discoveries. As an example, among of the earliest star catalogs were the lists of double stars initiated by John Michell in the 1760s. Michell was one of William Herschel’s mentors. Michell’s method of systematically logging the separations of double stars appealed to the detail-oriented Herschel.

Herschel systematically searched for double stars among "every star in the Heavens”. Out of this came the three largest double star catalogues known at the time. His initial catalogue in 1782 comprised 269 doubles or multiples. In 1784 he set about to re-observe his original catalogue hoping to spot changes in their positions or distances. In the process he added 484 more doubles and multiples, published as a second *Catalogue of Double Stars* in 1784. In 1822 he added a third catalogue of 145 systems discovered between 1783 and 1821. Visiting his original observations many years later, he noted that some had ever so slightly rotated around each other. It was the first demonstration that gravity acted beyond the system of planets known at the time.

Skip forward a century to Edward Charles Pickering, the director of the Harvard College Observatory from 1877 to 1919. One of the Observatory’s many duties was to compile catalogues of specific types of objects found on photographic plates. Photography had revolutionised astronomy, vastly widening the field-view of the sky. But when it came to understanding the way the cosmos works, dots on a plate were no better than dots in an eyepiece. They still need systematic classification. Pickering turned to his graduate students. All were male, in keeping with the practice of the time. Few women pursued astronomy, in theory because their “delicate constitutions” weren’t up to the arduous demand of siting still for hours in a freezing dome. Better they sit at a warm desk than at a cold eyepiece. That was the theory. In reality most women didn’t pursue astronomy because they knew they weren’t wanted.

There was historical precedent for women at a desk cataloguing for men at the telescope in the example of William Herschel and his sister Caroline. William couldn’t observe and write notes at the same time, so he inveigled Caroline into staying awake all night long to write down his words whenever he spotted something and hailed out its features. In winters Caroline sat in a small work hut below, huddled under blankets with a charcoal brazier on one side and a small window on the other. She would open the window whenever she heard her brother’s excited voice and diligently write down every word he uttered.

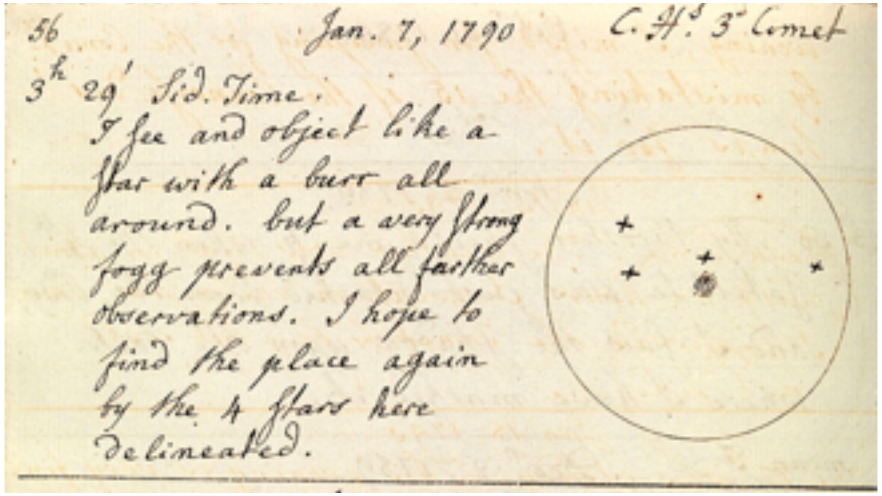


Fig. 5: The precedent of a desk-bound woman cataloguing astronomical data goes back as far as Caroline Herschel. This is one of her six comet discoveries.

Back at Harvard Observatory, Pickering grew frustrated and then fed up with his student cataloguers. Filling in boxes in a table or doing the tedious arithmetic of astronomical calculations was simply too boring for them. Popular legend has it that one day Pickering reached his limit and shouted at them, "My Scottish maid could do a better."

So he fired all the student computers and hired his Scottish maid, a woman newly arrived from her homeland named Williamina Fleming. Pickering had more respect for women's intelligence than did most men of the time. He knew that Fleming was a former teacher who had been forced into servitude after being abandoned by a feckless husband while she was still carrying her first baby.

Her official title was "computer", the common parlance for humans who converted data tables into numerical values. Fleming soon outperformed the graduate students—and for a fraction of the pay: 25 cents a day. Pickering suspected that there were many other women who would be just as detail-sensitive and diligent as Fleming, He settled on Henrietta Leavitt as his second assistant. As the number of astronomical plates multiplied, so did the volume of work. Fleming and Leavitt couldn't handle it all so Pickering sensibly asked Leavitt to hire other suitable candidates. Hire she did. Across three decades, dozens of "Leavitt's Ladies" compiled a vast database of astronomical calculations. The term "Harvard Harem" was used in certain circles for a time, but was eventually consigned to the intellectual antique shop.

Pickering mentored Harvard's first women Ph.D.s in astronomy. He argued for the advancement of all the women under his charge.

Yet despite this he placed budget over gender in his priorities. Women received $1,500 a year for their diligence, compared with $2,500 per year for male assistants — even those lacklustre males Pickering had fired.

One of Henrietta Leavitt's working colleagues was an outspoken woman named Williamina Fleming. Her main complaint about Pickering was, "He seems to think that no work is too much or too hard for me, no matter how long the hours. But let me raise the question of salary and I am immediately told that I receive an excellent salary as women's salaries stand. Doesn't he ever think that I have a home to keep and a family to take care of just the same as a men? I suppose a woman has no claim to such comforts. And this is considered an enlightened age!"

On matters other than equal pay Pickering was committed to women's professionalism. He was fair-minded and commendably open to progress. He wanted to nourish ability, to see credit properly attributed, and to advance astronomy. When he saw talent and accomplishment he did everything to advance it except pay for it.

In frustration over the issue of her meagre salary, Williamina Fleming groused in her diary, "I am told that my services are very valuable to the Observatory, but . . . I feel that my work cannot be of much account."

Pickering desperately needed Henrietta Leavitt to complete her observations of Cepheid variables — he even raised her wages to 30 cents/hour to prove his esteem. He agreed with Leavitt that Cepheids were standard candles when measuring astronomical distances.

Unfortunately Leavitt was in poor health and on leave to quietly recover. Vital or not, their correspondence had to rely on the postal mail. Their letters went back and forth, back and forth in time frames measured in weeks, and at times even months apart. Pickering even resorted to shipping fresh photographic plates for her to work on as she convalesced. Since the plates were made of thin glass, he was placing an apparently justified confidence in the care of the postal employees--not one was ever broken.

Henrietta Leavitt's work foreshadowed the discoveries of the more publicly acclaimed Edwin Hubble. Hubble leveraged Leavitt's law on the behaviour of variable stars to gauge distances to certain nebulae that he suspected were far more remote than astronomers thought. He was able to confidently conclude that many smudges in the sky were actually entire "island universes" or galaxies. He and others like him, male and female, extended the geography of the universe to millions of light-years.

When Leavitt eventually returned to the Harvard College Observatory, she could only work a few hours each day. She nevertheless took all the time she needed to ferret out what nobody else had managed to see. A sky watcher she was, a clockwatcher not.

In the end Leavitt showed that the glass ceiling had wafer-thin cracks. Pickering's women employees were blatantly overworked and underpaid, yet they loved their work. Annie Jump Cannon wryly put it: "I am not afraid of work, I jump for it."

The Harvard Computers' dedication to astronomy and to exactitude was a hallmark of their thinking. They endured scarlet fever, "grippe," (the flu), deafness, loneliness, and meagre pay. But they were also diligent enough to unravel a few mysteries of the universe.

> A straight line can readily be drawn among each of the two series of points corresponding to maxima and minima, thus showing that there is a simple relation between the brightness of the variables and their periods.
>
> Henrietta Swan Leavitt

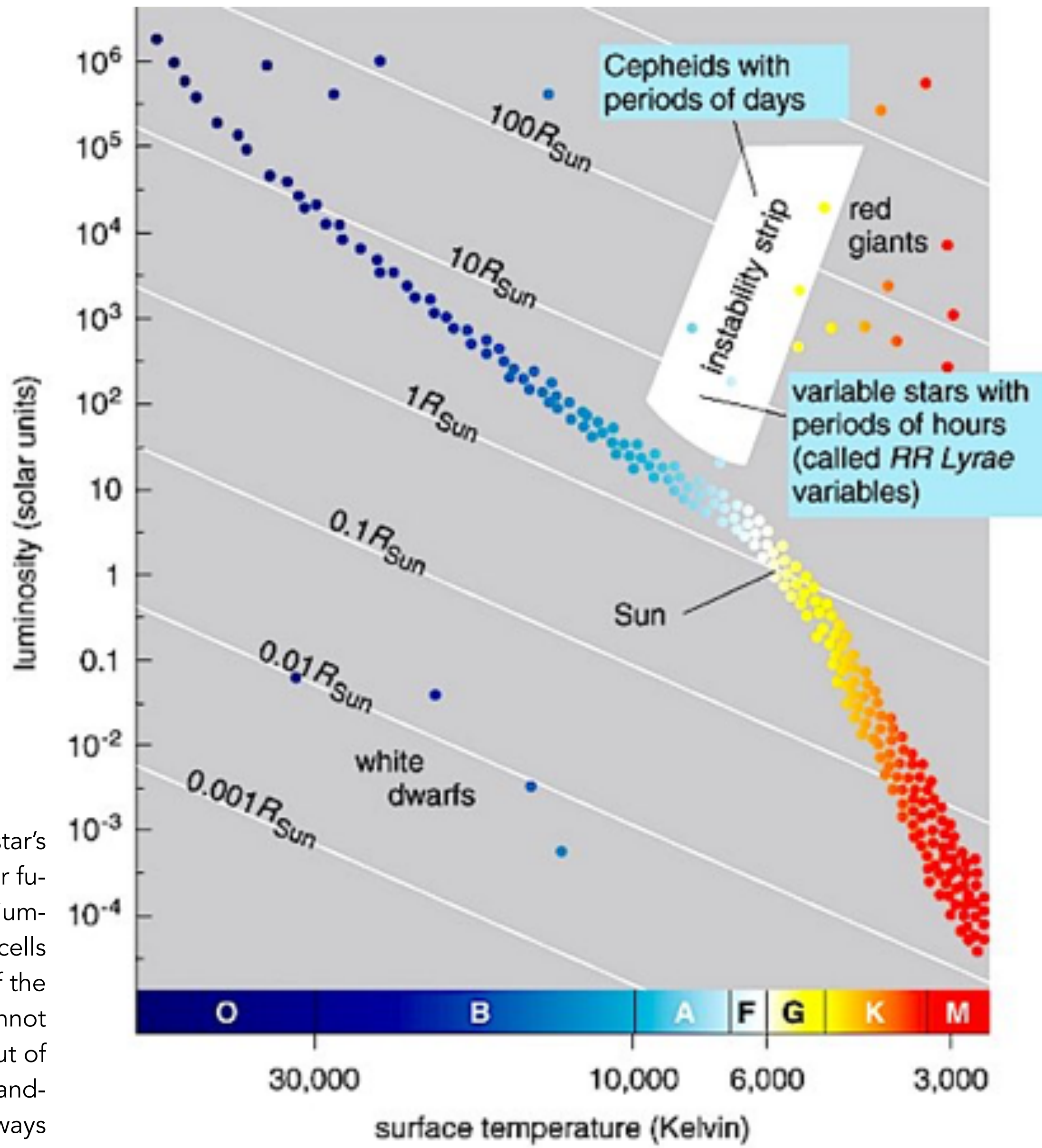
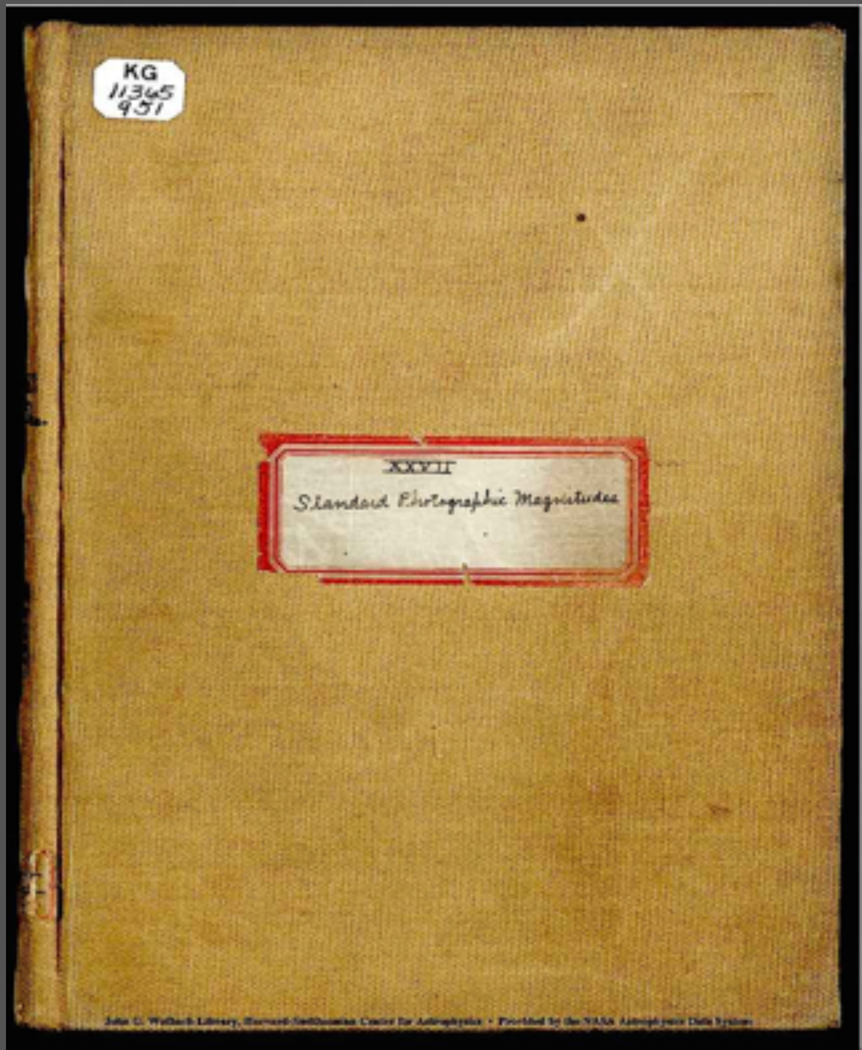


Fig. 6: A modern Hertzsprung-Russell Diagram (HRD) illustrates the stages in a star's lifetime during which fusion occurs in a shell surrounding the "ashes" of earlier fusion production — helium in hydrogen-burning stars, and carbon-oxygen in helium-burning cores. Shell-burning is unstable because it produces large convection cells in the star which circulate from deeply within the ash to as far as the surface of the star. So much deep interior heat is raised to the surface that the star's surface cannot immediately radiate it away. The star compensates by expanding, but gets out of balance. The only way the star can balance core heat and surface area is by expanding or contracting. Inevitably, given the enormous masses involved, the star is always a bit behind the curve. Cepheid phases can last many thousands of years.

Photometric logging in the bad old days



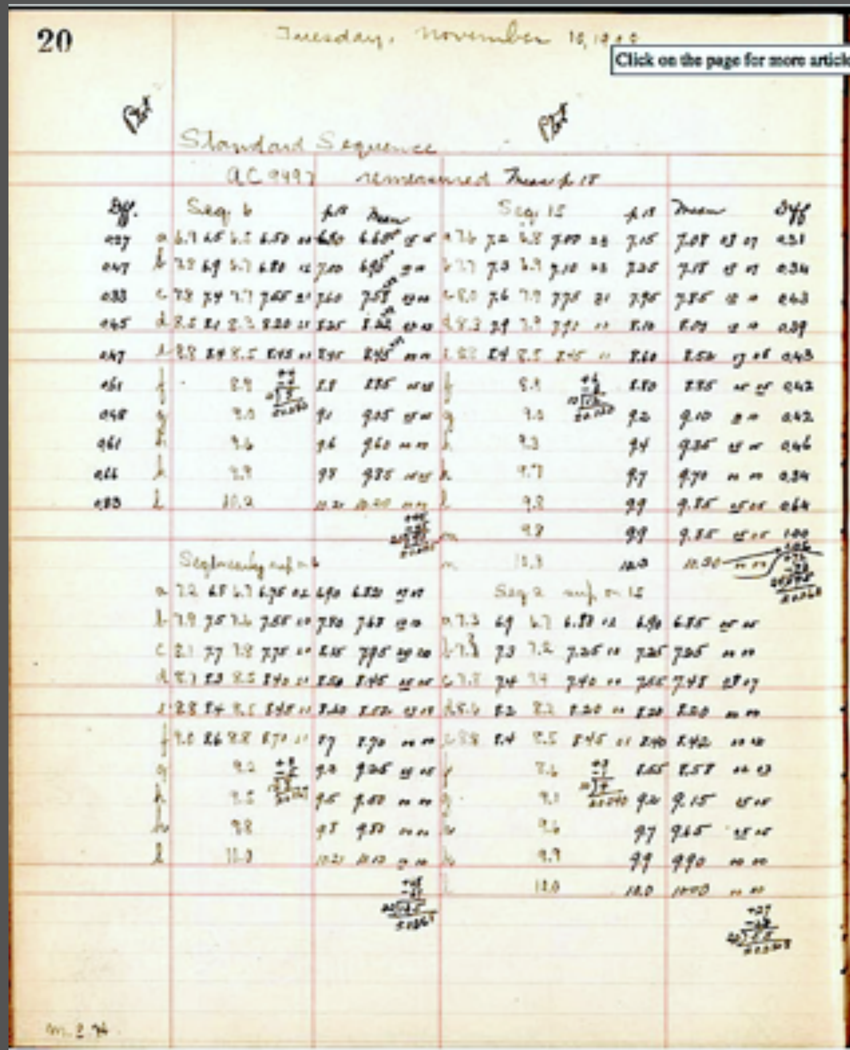


Fig. 7: Front cover and one of Leavitt's 48 handwritten pages of Cepheid period-luminosity calculations used as part of her *Standard Photographic Magnitudes* published by Harvard Observatory in 1908. Leavitt and her colleague "computers" did their complex arithmetic calculations using only pencil and paper. This in just one of the hundreds of data logs used to produce Leavitt's four landmark 1908 Cepheids papers as shown on the next two pages. The original logs, like this one in Leavitt's own hand, have never been converted into a digital database. By the time computers came along, all these entries had already been crunched into variable star light curves, among which were Leavitt's landmark Cepheid catalogs. Read more at: https://phys.org/news/2018-01-astronomers-years-stars-universe.html#jCp

1908: Henrietta's Annus Mirabilis

In a remarkable feat for any astronomer, Henrietta Leavitt published four landmark databases in a single year, 1908. The glass photographic plates were exposed by the 24-inch Bruce Telescope in Peru, and later by the Boyden Observatory in Bloemfontein, South Africa. Shipped by sea to Harvard, Pickering's team of "computers" first organised them by Right Ascension and Declination, then set about to minutely examine each plate. Their extensive lists were organised by the type of object in which they were found, and classified by a grid array of regions encompassing the entire object. The Large Magellanic Cloud alone boasted 1777 Cepheids

ANNALS OF HARVARD COLLEGE OBSERVATORY. VOL. LX. No. IV.

1777 VARIABLES IN THE MAGELLANIC CLOUDS.

BY HENRIETTA S. LEAVITT.

IN the spring of 1904, a comparison of two photographs of the Small Magellanic Cloud, taken with the 24-inch Bruce Telescope, led to the discovery of a number of faint variable stars. As the region appeared to be interesting, other plates were examined, and although the quality of most of these was below the usual high standard of excellence of the later plates, 57 new variables were found, and announced in Circular 79. In order to furnish material for determining their periods, a series of sixteen plates, having exposures of from two to four hours, was taken with the Bruce Telescope the following autumn. When they arrived at Cambridge, in January, 1905, a comparison of one of them with an early plate led immediately to the discovery of an extraordinary number of new variable stars. It was found, also, that plates, taken within two or three days of each other, could be compared with equally interesting results, showing that the periods of many of the variables are short. The number thus discovered, up to the present time, is 969. Adding to these 23 previously known, the total number of variables in this region is 992. The Large Magellanic Cloud has also been examined on 18 photographs taken with the 24-inch Bruce Telescope, and 808 new variables have been found, of which 152 were announced in Circular 82. As much time will be required for the discussion of these variables, the provisional catalogues given below have been prepared.

The labor of determining the precise right ascensions and declinations of nearly eighteen hundred variables and several hundred comparison stars would be very great, and as many of the objects are faint, the resulting positions could not readily be used in locating them. Accordingly, their rectangular coordinates have been employed. A reticule was prepared by making a photographic enlargement of a glass plate ruled accurately in squares, a millimetre on a side. The resulting plate measured 14 × 17 inches, the size of the Bruce plates, and was covered with squares measuring a centimetre on a side. Great care was taken to have the scale uniform in all parts of this plate, which was designed to furnish a standard reticule, not only for the Magellanic

Fig. 8

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 142.

28 NEW VARIABLE STARS IN HARVARD MAP, Nos. 30 AND 33.

AN examination, by Miss Leavitt, of Harvard Map, Nos. 30 and 33, has led to the discovery of 28 new variables. A summary of the results is contained in Table I, in which the successive columns give the number of the plate in the Harvard Map, the approximate right ascension and declination of the centre, the number of new variables discovered, the total number found, the proportion which is new, the whole number known, the probable number, the proportion of the probable number found, the probable number unknown, and the probable proportion unknown. The method of determining these various quantities is described in Circular 130.

TABLE I.

NUMBER AND DISTRIBUTION OF VARIABLES.

No.	Region. (h.)	Region. (°)	New Variables.	Total Found.	Proportion New.	All.	Probable Number.	Proportion Found.	Probable No. Unknown.	Proportion Unknown.
30	16	0	13	16	.93	23	112	.12	91	.81
33	22	0	15	18	.83	27	72	.25	45	.61

A list of the new variables is given in Table II. The designation, in the first column, is followed by the Harvard number, the constellation, the number in the Bonn Durchmusterung, the right ascension and declination for 1900, the brightest and faintest magnitudes observed, and the range. The known variables, R Serpentis, U Herculis, RU Librae, RR Aquarii, V Pegasi, and T Pegasi, were rediscovered.

The total number of stars in H. M. 30 is estimated as 14,000, and in H. M. 33, as 27,000. The number of known variables, therefore, in H. M. 30 is about one in 600, and in H. M. 33, one in 1,000. The total numbers of variables are probably one in 125, in H. M. 30, and one in 375, in H. M. 33. The proportion of variables

Fig. 9

ANNALS OF HARVARD COLLEGE OBSERVATORY. VOL. LX. NO. V.

TEN VARIABLE STARS OF THE ALGOL TYPE.

BY HENRIETTA S. LEAVITT.

THE discovery of variable stars, at this Observatory and elsewhere, has progressed so rapidly during the last five years, that the difficulty of keeping pace in observing and discussing them has become very great. In the study of distribution now in progress here, the actual time devoted to the search for new variables is small, but thorough observation requires much time, while the discussion of results may be prolonged almost indefinitely. When new lists of variables are published, therefore, it should be remembered that their discovery does not interfere materially with the study of individual objects. The number of these is so large that the publication of full results for all must be greatly delayed.

During the year 1906, the region thirty degrees square covered by Plate 50 in the Map of the Sky, Circular 71, was examined on a large number of photographs. A reproduction of a positive from this plate is given in Plate III. It includes one of the most densely crowded portions of the Milky Way. The Southern Cross, the Nebula surrounding η Carinae, the "Coal-Sack," and many other interesting objects appear on it. The positions and approximate magnitudes of the new variables found in this region are given in Circulars 79, 115, 120, 121, and 122, the total number announced being 97. Several of the variables appeared to belong to the Algol type, and were selected for immediate discussion. One of these, H 1255, probably varies continuously throughout its period, although in its brief minimum it resembles an Algol variable. Another, H 1289, has a secondary minimum and is perhaps of the type of β Lyrae. Apparently no sharp dividing line can be drawn between true Algol stars and those whose variations are continuous. Periods of nine variables in this region, which are of the Algol type or closely resemble it, have been determined, and are here discussed. One of these, SS Carinae, H 1232, was announced in Circular 115, but the examination of later photographs has made it possible to determine the period more accurately. The periods of three other variables were announced in Circulars 120 and 122, without giving the

Fig. 10

HARVARD COLLEGE OBSERVATORY.

CIRCULAR 141.

29 NEW VARIABLE STARS NEAR NOVA SAGITTARII.

In the study of the distribution of variable stars now in progress at this Observatory, an important line of research has for its object the discovery of groups of faint variables. At present, the most remarkable regions known are certain globular clusters, the Nebula of Orion, and the Magellanic Clouds. The investigation here referred to does not include the globular clusters. The photographs employed were taken with the 24-inch Bruce Telescope and have long exposures, preferably two hours, or more. The choice of the particular region to be examined at any time is guided principally by the number and quality of photographs available for comparison, preference being given to regions which are in themselves especially interesting. No attempt has been made to follow any consecutive order.

The region near Nova Sagittarii has recently been examined, by Miss Leavitt, on three Bruce plates having their centres for 1855, in R. A. $= 18^h 49^m$, Dec. $= -12°.5$; R. A. $= 18^h 54^m$, Dec. $= -12°.2$; R. A. $= 18^h 55^m$, Dec. $= -13°.4$. The corresponding plates, dates, and exposures are A 2845, October 23, 1897, 60^m; A 4091, October 26, 1899, 150^m; A 5712, October 10, 1901, 180^m. No two of the plates have the same centre. The region common to the three extends in right ascension, from $18^h 42^m$ to $19^h 2^m$, and in declination from $-10°.9$ to $-14°.7$, while the extreme limits of the region which may be compared on any two plates are $18^h 41^m$ and $19^h 7^m$ in right ascension, and $-10°.0$ and $-15°.0$ in declination. As there is much difficulty in comparing star images on superposed Bruce plates when the centres are a degree or more apart, it is not probable that all stars showing variation on these plates were discovered. Nevertheless, a surprising number of faint variables was found. The material existing for their confirmation is scanty, consisting principally of the three Bruce plates above mentioned, and three plates taken with the 8-inch Bache Telescope. The designations, dates, and exposures of these plates are, B 23759, August 2, 1899, 153^m; B 32278, July 17, 1903, 60^m; B 32341, July 28, 1903, 60^m. Seven other Bache plates were examined for a few

Fig. 11

Solving Cepheid Mysteries with the Magellanic Clouds

Tarini Konchady

Tarini is a second year graduate student at Texas A&M University, USA. She is currently studying Mira variables for better ways to calibrate the cosmic distance ladder.

Cepheid variables are definitely a gift to astronomers. They are a class of variable stars that are useful as distance indicators (objects that can help us measure distances because we know what their brightness ought to be if they were say 10 parsecs away from us). Henrietta Swan Leavitt was the first to notice that Cepheids that took longer to go from their brightest to their dimmest and back—that is, they had longer periods—tended to be brighter than Cepheids with shorter periods (see Figure 1). This relationship between period and brightness is called a period-luminosity relationship (PLR). We continue to use Cepheids to measure distances even though we still don't yet know everything about them.

Cepheids are broken up into two classes, generally speaking—Type I or Classical Cepheids, and Type II Cepheids. Type I Cepheids are younger than Type II Cepheids, and have a more structured light curve (see Figure 2) as well. There is also a third class of Cepheids that don't quite fit into either of the previous two classes called Anomalous Cepheids. The peculiarities of Type II Cepheids and Anomalous Cepheids have made understanding their origin and evolution an interesting problem. In this paper, the authors attempt to make headway on this issue by studying the spatial distribution of Cepheids and other variable stars called RR Lyrae in the Magellanic Clouds (Large: LMC, and Small: SMC, two of the largest satellites of the Milky Way).

The authors work with data taken of the Magellanic Clouds from the Optical Gravitational Lensing Experiment (OGLE). The data span 25 years, making the Clouds a hotbed for variable star identification. In this paper, nearly 10,000 Classical Cepheids and 50,000 RR Lyrae (another type of variable star that is a distance indicator) are used to constrain the positions of just under 350 Type II Cepheids and about 250 Anomalous Cepheids across both Clouds.

The main goal of the work is to check whether the location distributions of Type II Cepheids and Anomalous Cepheids are similar to the location distributions of (younger) Classical Cepheids and (older) RR Lyrae. If they are, then it's likely that the stars share similar origins. To do this, the authors first determined distances to the stars they were studying, and then used a statistical test to compare pairs of stars in the Clouds. The Type II and Anomalous Cepheids were paired with Classical Cepheids and RR Lyrae. To save on computing time, the authors compared the less understood variables with 1000 samples of better understood variables. The samples were independent of each other, and were drawn from the available Classical Cepheids and RR Lyrae. Each sample contained three times as many Classical Cepheids and RR Lyrae than Type II and Anomalous Cepheids.

To determine the distances to their stars, the authors used the stars' periods and Wesenheit indices to obtain a PLR and then a distance modulus (see Figure 3). Wesenheit indices or functions can be used in place of magnitude, and navigate the user around the effects of things like interstellar dust that can cause objects to appear redder than they actually are (see this Astrobite for more on them). They do require that an object was observed in at least two filters.

Publication data and abstract of the Astro-ph paper arXiv:1809.01338 reviewed by Tarini Konchady

The three-dimensional distributions of Type II Cepheids and Anomalous Cepheids in the Magellanic Clouds. Do these stars belong to the old, young or intermediate-age population?

P. Iwanek, I. Soszyński, A. Udalski, M. K. Szymański, S. Kozłowski, P. Pietrukowicz, D. Skowron, J. Skowron, P. Mróz, R. Poleski, A. Jacyszyn-Dobrzeniecka. Submitted to *Acta Astronomica*, Warsaw University Observatory 5 Sep 2018.

The nature of Type II Cepheids and Anomalous Cepheids is still not well known and their evolutionary channels leave many unanswered questions. One of the characteristic features directly related to the age of stars is their spatial distribution. We use complete collection of classical pulsating stars in the Magellanic Clouds discovered by the OGLE project, to compare their spatial distributions. In this analysis we use 9649 Classical Cepheids (DCEPs), 262 Anomalous Cepheids (ACEPs), 338 Type II Cepheids (T2CEPs) and 46 443 RR Lyrae stars (RR Lyr) from both Magellanic Clouds. We compute three-dimensional Kolmogorov-Smirnov tests for every possible pair of T2CEPs and ACEPs with DCEPs, and RR Lyrae stars.

We confirm that BL Her stars are as old as RR Lyr variables - their spatial distributions are similar, and they create a vast halo around both galaxies. We discover that spatial distribution of W Vir stars has attributes characteristic for both young and old stellar populations. Hence, it seems that these similarities are related to the concentration of these stars in the center of the Large Magellanic Cloud, and the lack of a vast halo. This leads to the conclusion that W Vir variables could be a mixture of old and intermediate-age stars. Our analysis of the three-dimensional distributions of ACEPs shows that they differ significantly from DCEPs. Statistical tests of ACEPs distributions with RR Lyr distributions give ambiguous results. We consider that these two distributions can be similar

Spatial Sorts of Stars

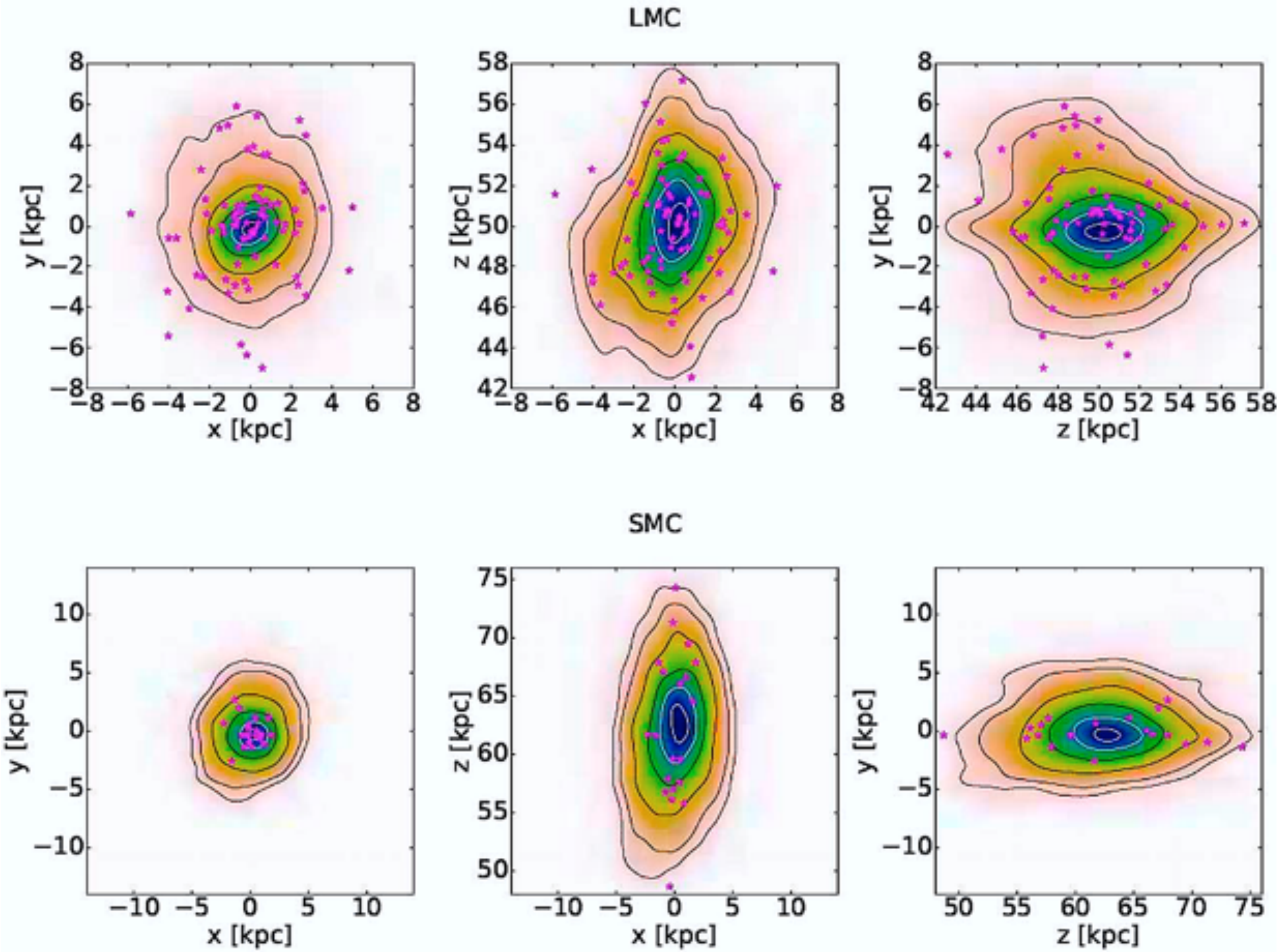
After pairing off the stars and checking their spatial distribution relative to that of the Classical Cepheids and RR Lyrae, the authors arrive at three distributions (see Figure 4):

- *BL Herculis* (a subgroup of Type II Cepheids) stars have a distribution similar to RR Lyrae in both the LMC and the SMC. It seems that they may also have a distribution similar to Classical Cepheids in the SMC but this might be due to the fact that there are very few Type II Cepheids to work with in that Cloud. This result suggests that BL Herculis stars are old and likely close to the age of the RR Lyrae in the Clouds.
- *W Virginis* (another subgroup of Type II Cepheids) stars appear to be similar to Classical Cepheids in distribution. They are a tad more perplexing—most of them appear to lie in regions with young stars but some of them appear in regions that exclude young stars. Approximating their relationship to RR Lyrae suggests that these stars are likely intermediate age, or a mix of old and intermediate age stars between the RR Lyrae and the Classical Cepheids.
- *Anomalous Cepheids* are wily, and don't appear to trace the distribution of Classical Cepheids. Comparing them to RR Lyrae suggests a kinship but more with the ab RR Lyrae than the c RR Lyrae. The Anomalous Cepheids live in the outer regions of the both the LMC and the SMC, which suggests that they are of an older population like the RR Lyrae.

The authors call the results from the LMC more reliable since it simply has more stars than the SMC. Anomalous Cepheids are still ambiguous about their origins but these results suggest that they might be created from binary systems of two low mass stars.

While we don't yet fully understand how these strange Cepheids evolve, this paper points us in the right direction to learn more. Given how important Cepheids are to constraining the Hubble Constant and understanding how the Universe expands, this is an important problem yet to be solved.

Fig. 1: Spatial distribution of BL Her stars in comparison to the distribution of RRab stars. The *top panel* presents Cartesian projections for the LMC and the *bottom panel* presents the SMC. We estimate shapes of the galaxies in each projection using standard kernel density estimation (KDE) and RRab stars, which are marked with colour map. Additionally, in each projection we plot normalized density contours. From the center of the galaxies to the edge, we plot normalized density with value: 95% (first white contour), 75% (second white contour), 50%, 25%, 10%, and 5%. We marked BL Her stars with magenta points.



Addendum by *Nightfall* editor:

Leavitt & Pickering's foundational 1912 paper describing the period-luminosity (P/L) relation in Cepheid variables inspired many years of research into their typologies and causes. The effort was fundamental because classical Cepheid-type pulsators were the most reliable distance indicators in the nearby Universe. Subsequent studies by Baade (1952) discovered that there are in fact two different groups of Cepheids, each of which exhibits

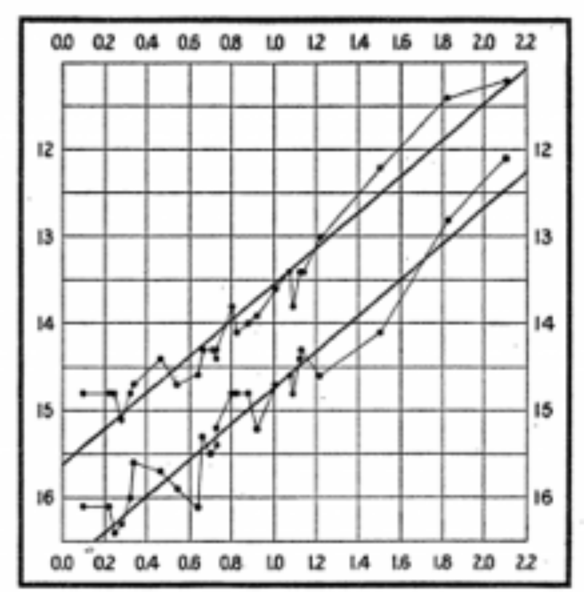


FIG. 2.

Fig. 2: The Period-Luminosity Relationship of Cepheid variables identified by Henrietta Swan Leavitt in the Small Magellanic Cloud. The *x*-axis is the logarithm of the Cepheid periods in days; the *y*-axis is the apparent magnitude. The upper plot is the maximum brightness of the Cepheids; the lower plot is their minimum brightness [originally shown as Figure 2 in Leavitt & Pickering (1912)]

different P/L relations. Cepheids were first divided into Population I or Classical Cepheids (DCEPs) and Type II Cepheids (T2CEPs). Subsequently T2CEPs were divided into three subgroups depending on their pulsation periods: *BL Herculis* (BL Her; P < 4 d), *W Virginis* (W Vir; P < 20 d), and *RV Tauri* (RV Tau; P > 20 d).

The boundaries in the pulsation periods for these stars are not strict, and some of these groups partly overlap. In 2008 Soszynski et al. distinguished a fourth subgroup of T2CEPs, named *peculiar W Virginis stars* (peculiar W Vir).

After six decades of T2CEP studies their origin and evolution are still not clear. The first evolutionary scenarios were proposed by Gingold (1976, 1985). The most up-to-date review of the T2CEPs properties is Welch (2012). These objects are now believed to be low-mass stars belonging to the halo and old disk stellar populations. BL Her stars are thought to move from the blue horizontal giant branch up to asymptotic giant branch, though the mechanism is not clear. During the transition BL Her stars become brighter and their radii increase, the only cause of which would be helium burning in the cores. BL Her variables pass through the instability strip at luminosities which correspond to the pulsation periods shorter than our days.

RV Tau variables are post-asymptotic giant branch stars moving toward the massive ejection of their outer envelope into a planetary nebula, leaving behind a white dwarf. These stars pass through the high-luminosity extension of the Cepheid instability strip which corresponds to pulsation periods longer than 20 days.

The evolution of W Vir stars is problematic. These are asymptotic giant branch stars that have exhausted helium in their cores and have initiated shell burning helium. Helium burning in the shell reduces the energy supply of the hydrogen shell burning just above it, and the hydrogen shell turns off. Later on the hydrogen shell re-ignites from the compressive heating caused by gravitational contraction. When these behaviours occur in both shells the stars blue-loop into the instability strip. The loops are visible in stars with thin outer envelopes which allow enough fusion photons escape without re-absorption/emission for our detectors. At present the detailed steps in this evolutionary model are not clear (Groenewegen & Jurkovic, 2017a). *=DB*

Leavitt's living Legacy II: Kate Hartman

A hundred years and Leavitt's Law is still going strong


Our understanding of the universe is based on knowing the distances to other galaxies, yet this seemingly-simple fact turns out to be rather more difficult to prove. The best tool was discovered over 100 years ago from an astronomer who was mostly unheralded in her time—Henrietta Swan Leavitt.

Today, a modern young successor to Henrietta Leavitt has used Sloan Digital Sky Survey (SDSS) data to make Levitt's original distance measurements more precise than ever.

"It's been fascinating to work with such historically significant stars," says Kate Hartman, an undergraduate from Pomona College in Southern California, who announced her results at the 2018 American Astronomical Society (AAS) meeting in National Harbor, Maryland. Hartman revisited Leavitt's Cepheid variables using the far more accurate photometry of Hipparcos and now Gaia data.

The variable star pattern was first noticed in 1784 in the constellation Cepheus, so these stars became known as Cepheid variables.

Thanks to the work of Henrietta Leavitt in the early 1900s, Cepheid variables went from mere curiosities to indispensable tools. Leavitt's contributions were largely ignored for one simple reason—she was a woman at time when women were not taken seriously by other astronomers.

Leavitt died from cancer at age 53, unacknowledged as the discoverer of the key to determining distances to such stars anywhere, whether in our Milky Way or in a remote galaxy. Using Leavitt's period-luminosity relationship astronomers could calculate the distances to Cepheid variables in galaxies far beyond our own Milky Way. That in turn made possible the discovery that the entire universe is expanding — a discovery that would not have been possible without the Leavitt Law.

Now, more than a century later, astronomers like Kate Hartman are carrying on Leavitt's work. Hartman's announcement came about as a result of a ten-week summer research project at Carnegie Observatories. Hartman used the Sloan Digital Sky Survey's Apache Point Galactic Evolution

Experiment (APOGEE), which is systematically mapping the chemical compositions and motions of stars all across the galaxy. The APOGEE survey is optimised to study the cool, old red giant stars found everywhere in the galaxy. Some of them are in their unstable Cepheid phase in which gigantic convection bubbles dredge core matter all the way to the surface. Cepheid variables are similar to each other in temperature, so they are well suited for the APOGEE survey.

Kate Hartman realised that Cepheid variables were key to the success of the APOGEE survey and therefore represented an ideal opportunity to recalibrate Leavitt's Law. APOGEE had the additional fillip of providing astronomers with a tool to map young stars in the same way they map old giant stars. Mapping these two types of stars simultaneously enables astronomers like Hartman to compare structures from the ancient parts of our Galaxy in the bulge to more recently-formed components in the spiral arms. Cepheid variables offer tremendous insight into the structure of our galaxy.

But such insight comes with complications. The very property of the stars that enabled Henrietta Leavitt to discover the Leavitt Law — the predictability of their swings in brightness — also created challenges for the APOGEE mission. Over a pulsation cycle of a Cepheid variable, the star's properties change. Their temperature, surface gravity, and atmospheric properties vary greatly over a fairly short time. So how can APOGEE properly measure them? Kate Hartman thought it would be an excellent summer research project for her. It beats beers and suntan lotion at the beach.

Hartman was able to demonstrate that it is possible to get consistent measurements of the chemical makeup of Cepheid variables, regardless of when in their cycle they were observed. She undertook to analyse multiple spectra from the same Cepheid variables and measure the amount of different elements in their spectra — a comparative metallicity distribution.

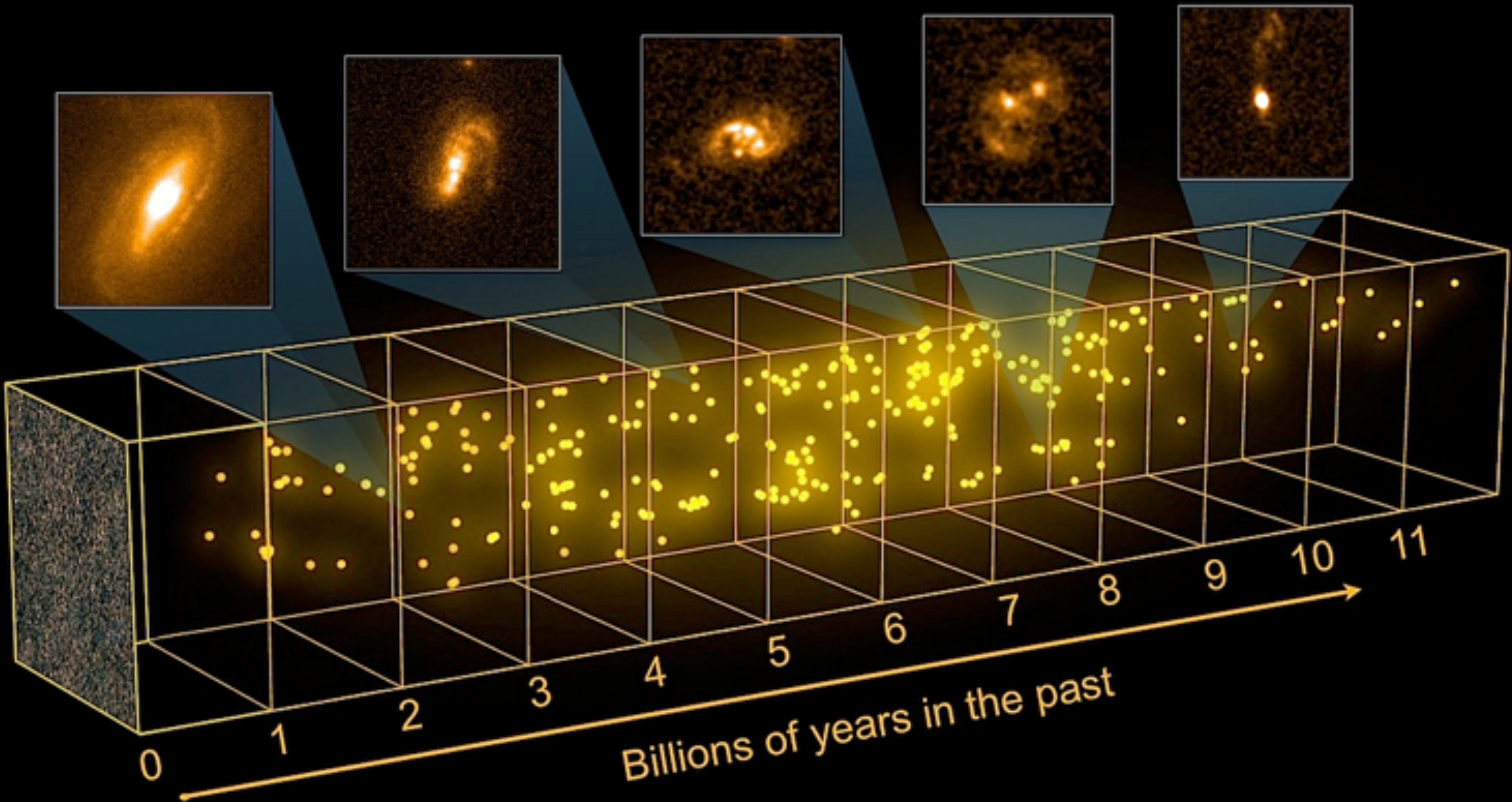
When she looked at a star's spectrum across its entire pulsation cycle, she found no significant differences in the results. That supported the reliability of her methodology. Certain that APOGEE could reliably measure Cepheid variables was important because it was the first survey to record so many Cepheids so regularly in so many places. APOGEE operates simultaneously with twin instruments on telescopes in both the Northern and Southern hemispheres, hence it encompasses the entire Milky Way galaxy and the Large and Small Magellanic Clouds as well. Cepheids can be observed in very different chemical environments, using the same instrument and data analysis process every time.

As a result of Hartman's findings, additional APOGEE observations of Cepheid variables were designed to expand on her findings. Jen Sobeck of the University of Washington, APOGEE's Project Manager, explains, "the survey will observe the most nearby and well studied Cepheids with observations several times a month, will target Cepheids in the Large and Small Magellanic Cloud, and will eventually target all Cepheids in all parts of the sky we observe. These observations are an important enhancement to the original APOGEE map of the galaxy."

Now the ESA Gaia mission provided direct trigonometric parallax distances to more than a billion stars in our galaxy. Now APOGEE's spectroscopy rests as the final piece in the puzzle discovered by Henrietta Leavitt in 1908. APOGEE has provided an accurate calibration of the Leavitt Law in Cepheid variable stars throughout the Milky Way and its neighbours. With all these new tools at their disposal, astronomers will be able to follow up on the work of astronomers like the century-bridging Henrietta Leavitt and Kaye Hartman for generations to come.

Source: *PhysOrg 10 Jan 2018*.

Henrietta's legacy: 1912 – 2018



Source: phys.org

A Radio Bright Quasar at the Edge

Joshua Kerrigan

Josh is a 5th year PhD student at Brown University studying the early universe through the 21cm neutral hydrogen emission, using the Precision Array for Probing the Epoch of Reionization (PAPER) and the Hydrogen Epoch of Reionization Array (HERA) radio interferometer arrays.

Quasars are some of the most interesting astronomical objects, able to provide us with information across both astrophysics and cosmology. When a quasar with unique properties, such as being exceptionally luminous is discovered, it's particularly eye-catching. This is because it can provide an opportunity to make measurements that wouldn't be possible otherwise.

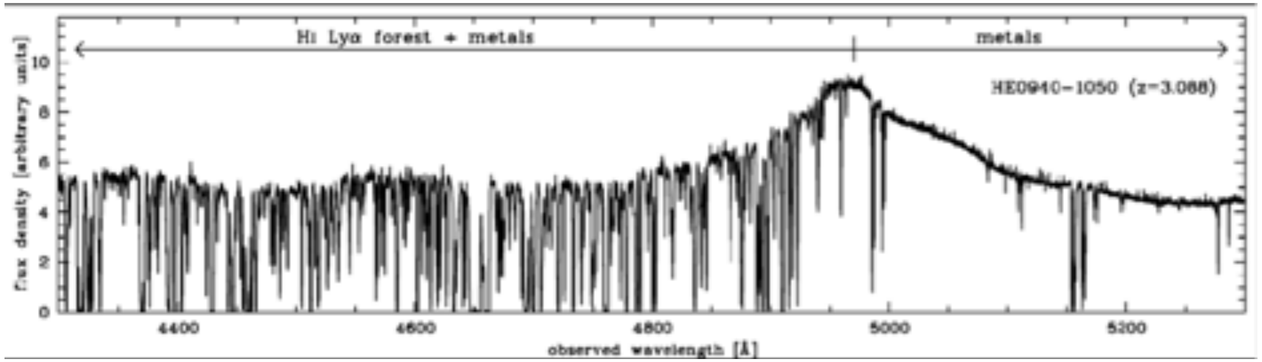


Fig. 1: *Flux density of a quasar emission across observed wavelengths.* The rapidly varying peaks from ~ 4300 to 4900 Angstroms is known as the Lyman Alpha Forest, where dips correspond to neutral hydrogen that have absorbed Lyman Alpha photons.

What's all the fuss about quasars?

Astronomers look to quasars because of the extreme conditions surrounding their existence. They are exceptionally bright and emit across the entire span of the electromagnetic spectrum. These luminous emissions are thought to be due to the accretion of gas onto a supermassive black hole at the center. So you might be asking yourself, if these are so bright, why do we even need telescopes to see them? Well that's because most quasars are at incredible distances, located at redshifts of $z > 0.1$, meaning relative to anything local to us, they'll appear very dim. In fact the closest quasar to us, *Markarian 231*, is still at a measurable redshift of z=0.04 at B mag. 14.7.

What we want to highlight today are quasars on the opposite end of that spectrum, those that are very far away, at high redshift. These types of quasars can give us direct probes to intermediate periods in the Universe's history, like a certain epoch that may have left the Universe reionized. One way a quasar can tell us about the timeline of the Universe is through the *Lyman alpha Forest*, which provides us with hints about neutral hydrogen content in the intervening *intergalactic medium* (IGM). This happens when higher energy UV emissions (shorter wavelength than the Lyman Alpha line) from high redshift galaxies get redshifted into the Lyman Alpha absorption range. This leaves dips in the flux density when observed here on Earth. We can directly relate these dips in the flux density to the redshift location of neutral hydrogen.

Cosmic Reionization

The *Epoch of Reionization* (EoR) is a period in cosmic history when neutral hydrogen from the early universe became reionized. This was due to the earliest stars and galaxies generating an abundance of ionizing UV radiation which systematically reionzied the surrounding hydrogen beginning somewhere around a redshift of 12 (300 Myr after the Big Bang). This process, based on our best "guess", has reionization completing somewhere in the region of redshift 6. Having a rough idea when the EoR ended gives us a great starting point to begin searching for additional evidence of the reionization process. Thus why we are very excited about discovering quasars at very high redshift, because they can directly probe the amount of neutral hydrogen present in the IGM.

Now moving onto the new discovery, the radio brightest high redshift quasar PSO J352.4034-15.3373. Only 15-20% of all quasars are considered radio loud, meaning that radio emissions are the brightest components of the quasar spectrum.

Publication data and abstract of the Astro-ph paper arXiv:1807.02531 reviewed in astrobites by Joshua Kerrigan

[*A powerful radio-loud quasar at the end of cosmic reionization*]

Eduardo Banados, Chris Carilli, Fabian Walter, Emmanuel Momjian, Roberto Decarli, Emanuele P. Farina, Chiara Mazzucchelli, Bram P. Venemans

We present the discovery of the radio-loud quasar PSO J352.4034-15.3373 at *z*=5.84 pm 0.02. This quasar is the radio brightest source known, by an order of magnitude, at *z*~6 with a flux density in the range of 8–100 mJy from 3GHz to 230MHz and a radio loudness parameter R>~1000. This source provides an unprecedented opportunity to study powerful jets and radio-mode feedback at the highest redshifts, and presents the first real chance to probe deep into the neutral intergalactic medium by detecting 21 cm absorption at the end of cosmic reionization.

(Submitted to Astro-ph on 6 Jul 2018. Accepted by *The Astrophysical Journal* 8 May 2018.)

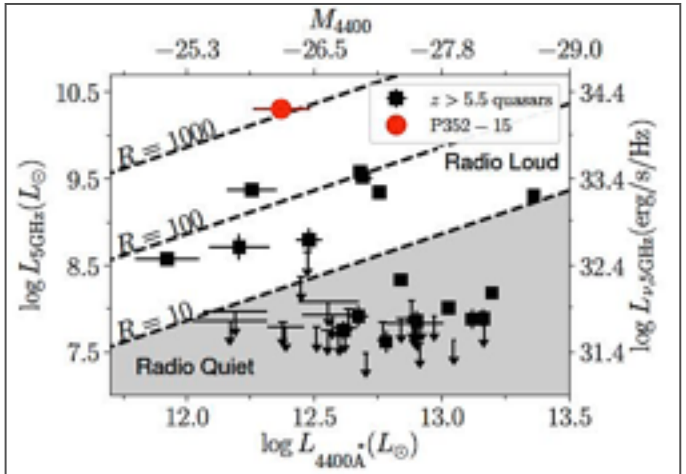


Figure 4. Rest-frame 5 GHz radio luminosity vs. rest-frame 4400 Å optical luminosity for all redshift $z > 5.5$ quasars detected at 1.4 GHz or with strong limits (figure adapted from Bañados et al. 2015). The arrows represent 3σ upper limits. The red circle corresponds to P352–15, the quasar discussed in this Letter. We show the average of the radio luminosity using two radio slopes ($\alpha = -0.89$ and $\alpha = -1.06$). We note that the symbol size is bigger in the y-axis than the whole range allowed by the two radio slopes (see also Table 1).

Fig. 2: The relative log luminosities of quasars at 4000 Angstroms to radio emissions at 5GHz. This shows that the quasar P352-15 is radio brightest of all competing high redshift quasars. [Figure 4 in the paper.]

The brightest quasar to date

This newly discovered quasar, which was determined to be at redshift z=5.82, has a radio flux density an order of magnitude greater than the next best radio loud high redshift quasar (Fig. 2 prev. page). The peak flux density of PSO J352-15 was measured to be approximately 100 mJy in the observing frequencies of 3GHz to 230MHz. In comparison, Cygnus A, one of the brightest radio galaxies nearby has a flux density on the order of 10–100 Jy, which demonstrates why these high redshift quasars are difficult to see.

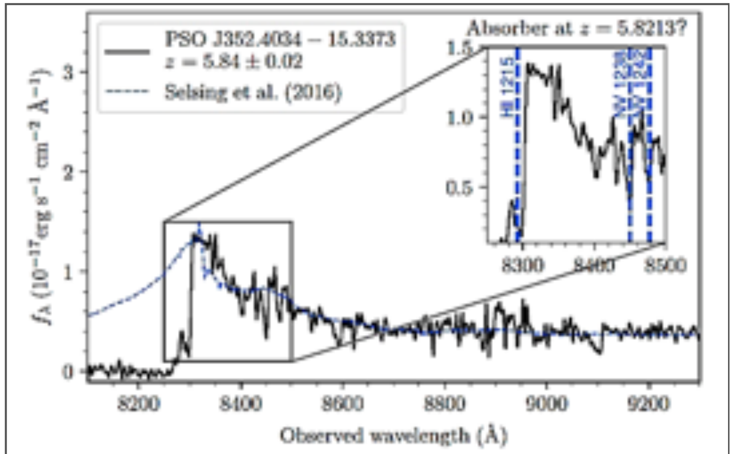


Figure 1. Discovery spectrum of the radio-loud quasar P352–15 at $z = 5.84 \pm 0.02$. The dashed line is the quasar template from Selsing et al. (2016) at the redshift of the quasar for comparison. The inset shows a zoom-in indicating the tentative detection of an associated absorber at $z = 5.8213$.

Fig. 3: Flux density measurement over observed wavelengths of the quasar PSO J352.4034-15.3373. A sharp drop-off at a wavelength of ~8300 Angstroms indicates that between us and the quasar is a very dense Lyman alpha absorbing environment. [Figure 1 in the paper.]

Of particular interest to reionization is the spectroscopic follow-up of PSO J352-15. In Figure 3 we can see that compared to the quasar template (blue dashed line), there is a sharp drop-off in flux density at 8300 Angstroms. Similar to the Lyman Alpha Forest mentioned before, this sharp absorption feature hints to a dense nearby environment, which means lots of neutral hydrogen. This interesting feature of PSO J352-15 puts it in a good position to probe for 21cm EoR measurements using radio telescopes such as the *Murchison Widefield Array* or *Giant Meterwave Radio Telescope*.

Going beyond cosmological implications, the authors additionally point to future potential studies for PSO J352-15 that could include radio-jet measurements to understand how supermassive black holes form, and how important *radio-mode feedback* is to the earliest galaxies. To see additional information on PSO J352-15 you can check out the *companion paper* which goes into the components and morphology of the quasar.

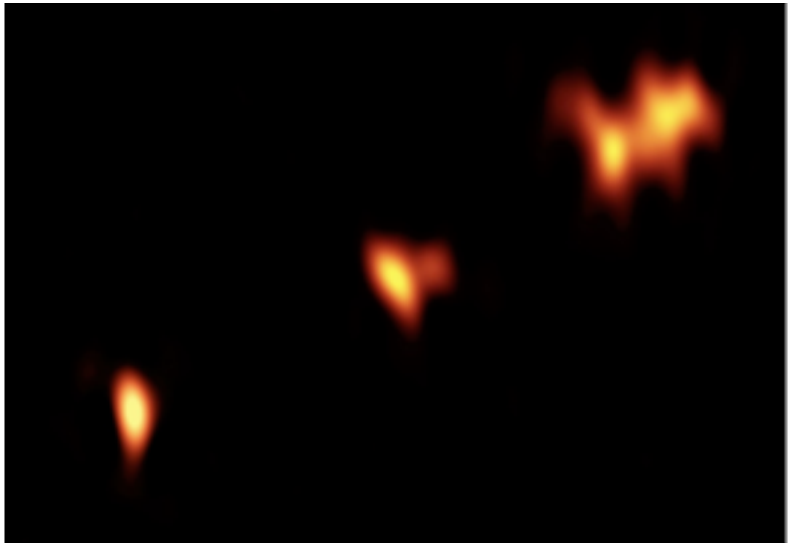


Fig. 4: VLBA image of the newly discovered z=5.84 quasar PSO J352.4034-15.3373 three main components of the object are seen; two of them show substructure. *Image credit*: Momjian et al. NRAO.

Editor’s addendum: About the Lyman-alpha forest:

The spatial structure, thermodynamic properties and chemical composition of the warm intergalactic gas is studied using quasar absorption lines and X-ray observations of the hot intercluster gas. In comparison with simulations we can investigate the early stages of galaxy formation and its back reaction on the cosmic environment.

Neutral hydrogen is widely distributed over the cosmos, absorbing the radiation of distant quasars. This manifests itself as "forest" of absorption lines in the spectra of these quasars. Studying the distribution of this intergalactic matter allows us to constrain the formation of large-scale structures in the universe. The identification of heavy element absorption lines in quasar spectra provides us with insights into the enrichment of intergalactic gas with the products of stellar nucleosynthesis. We have analysed a large sample of high resolution quasar spectra obtained with the Very Large Telescope (VLT) from the ESO and applied these data for a multitude of cosmological applications.

In the immediate vicinity of luminous quasars, the absorption spectra experience a remarkable change. Hard UV radiation from the quasars ionises the remaining neutral hydrogen and reduces the absorption. Thus, the intergalactic medium in the vicinity of quasars becomes more transparent: This is the so-called "Proximity Effect".

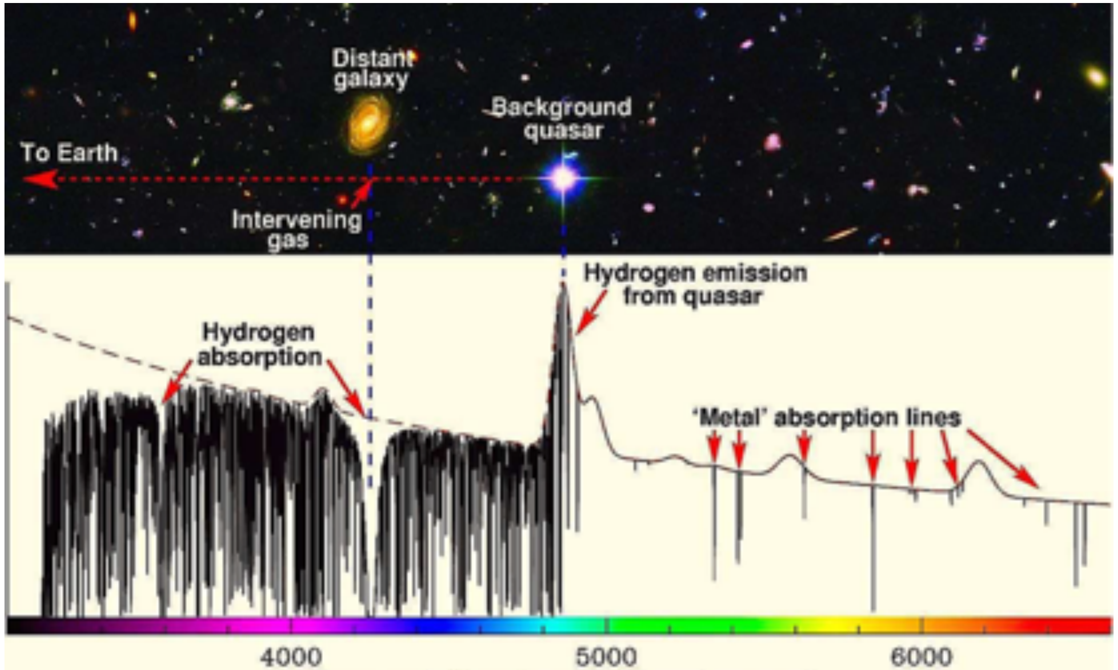


Fig 5: Lyman-alpha forest compared with typical Lyman-alpha absorbing objects. *Image source: Cosmology and Large-Scale Structure*, Leibniz Institute for Astrophysics Potsdam.

We have searched for this phenomenon in a large sample of VLT quasar spectra, and for the first time we could significantly detect the Proximity Effect in all individual quasar spectra. This permitted us to determine the mean intensity of the metagalactic UV radiation field.

Below we show the high-resolution spectrum of the quasar HE 0940-1050, obtained with the UVES spectrograph at the ESO-VLT. The range of the hydrogen Lyman forest lines is indicated. Other absorption lines are due to heavier elements (“metals").

If a foreground quasar lies apparently close to the line of sight of another background quasar, a "transverse" Proximity Effect might be expected under certain circumstances (however, this effect was not observed until now). We have combined optical and ultraviolet spectra to estimate the "spectral hardness" of the ionising UV radiation field as a function of redshift. We found that this hardness is particularly high close to each of the considered foreground quasars. This is the first detection of the "transverse Proximity Effect in spectral hardness", stating that the hard UV radiation of individual quasars is detectable even over cosmological distances. *Text source: Leibniz Institute*. =DB

How heavy is our galaxy?

Nora Shipp
Nora is a a 2nd year grad student at the University of Chicago. She works on combining simulations and observations of the relation between the Milky Way and dark matter.

Weighing a Galaxy is not an easy task. The Milky Way is a complicated mess of stars and gas, and – to make things even more difficult – the majority of our Galaxy is invisible in the form of dark matter (Fig. 1). A precise measurement of the mass of the Galaxy is essential for understanding the physics of galaxy formation and for unraveling fundamental cosmological mysteries like the nature of dark matter.

The Thomas Callingham et al. paper reviewed here proposes that current calculations of the mass range from about 500 billion to 2.5 trillion times the mass of our sun. The difference between these two huge numbers is only a factor of a few.

The exact number is important to pin down because our Galaxy is such a unique laboratory for studying the mysteries of the Universe. Ours is the only galaxy we can observe from up-close, and thereby collect detailed information on its structure and the physical processes that occur within it. This snapshot of a single galaxy can be generalised to overarching physical theories combined with observations of distant galaxies, and compared to theoretical predictions from numerical simulations. This generalisation, however, depends on our ability to place the Milky Way in the context of the general galaxy population – and that requires a precise measurement of the mass of our Galaxy.

Title: *The mass of the Milky Way from satellite dynamics*
Authors: Thomas Callingham, Marius Cautun, Alis J. Deason, Carlos S. Frenk, Wenting Wang, Facundo A. Gómez, Robert J. J. Grand, Federico Marianacci, Rüdiger Pakmor
First Author's Institution: Institute of Computational Cosmology, University of Durham, UK
Submitted 30 Aug 2018 to MNRAS open access. Available on Astro-ph.

So, how is it possible to weigh a Galaxy from within? The authors of today's paper measure the mass of the Milky Way based on the motions of orbiting satellite galaxies (Fig. 2). Just as we can use the orbital speeds of the planets in our solar system and Newton's law of gravitation to infer the mass of the Sun, we can use measurements of the orbits of small satellite galaxies around the Milky Way to weigh our Galaxy.

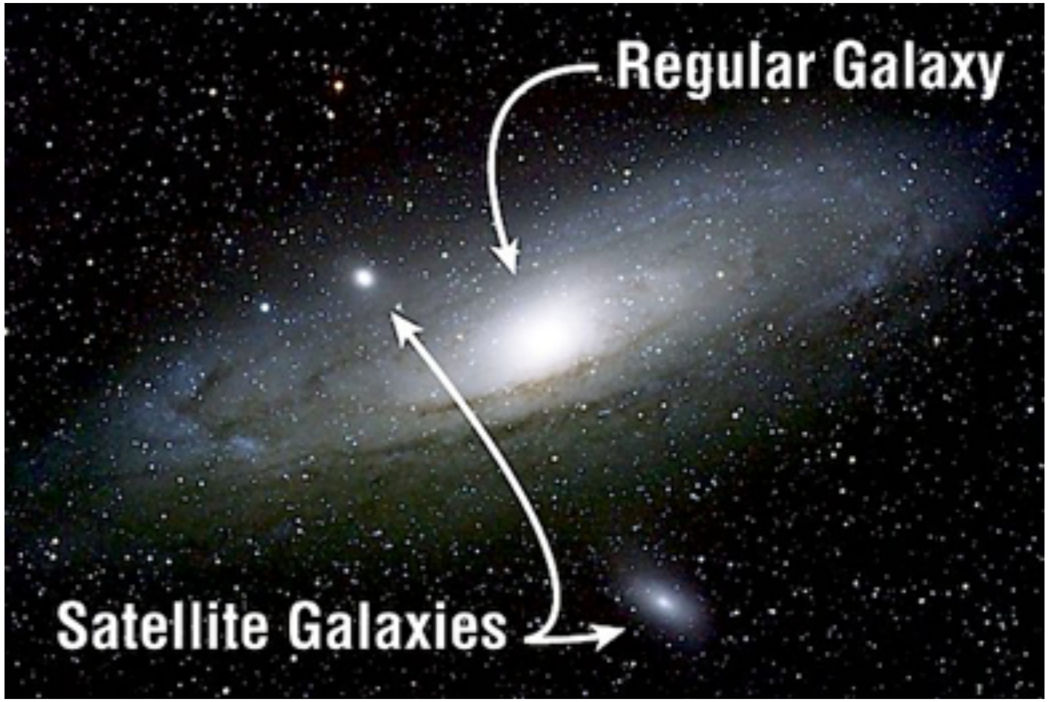
Although the general concept is the same, weighing a galaxy is much messier than weighing a star. The mass in the Milky Way is spread out over a huge volume, complicating the calculation. Instead of calculating the mass analytically, the authors take advantage of complex galaxy formation simulations. By comparing the distribution of satellite galaxy orbits in the Milky Way to those of simulated galaxies of various masses they were able to tightly constrain the mass of the Milky Way.

The authors use a clever trick to obtain a more precise estimate. Numerical simulations require considerable computational power, so the number of simulated galaxies is limited. The *EAGLE simulations*, for example, contain a relatively small number of galaxies at masses similar to the Milky Way.

Even for a specific galaxy's mass there is significant variation in the behaviour of satellite galaxies. Accurate predictions require a large sample.

To increase their sample size, the authors use the fact that the energies and momenta of satellites follow a simple relationship with the mass of the galaxy - they are both proportional to $M^{2/3}$. The satellite properties can therefore be adjusted to correspond to different masses, increasing the sample size. This simple trick allows for a larger sample of realistically simulated galaxies at a range of masses to compare to the satellite properties of the Milky Way.

This clever method, combined with state of the art data and powerful simulations allowed the authors to obtain a measurement of the mass of the Milky Way of about 1 trillion times the mass of the sun, with an uncertainty of only 20% (*Fig. 3*)! The number is within the range of alternate measurements, but is more precise than most previous values (*Fig. 4*). This measurement will continue to improve as more satellite galaxies are precisely measured and included in the calculation. As the mass of our Galaxy is more tightly pinned down we will be able to place stronger constraints on exciting physics, including the role of feedback in galaxy formation, the predicted number of satellite galaxies around the Milky Way, and the nature of dark matter.



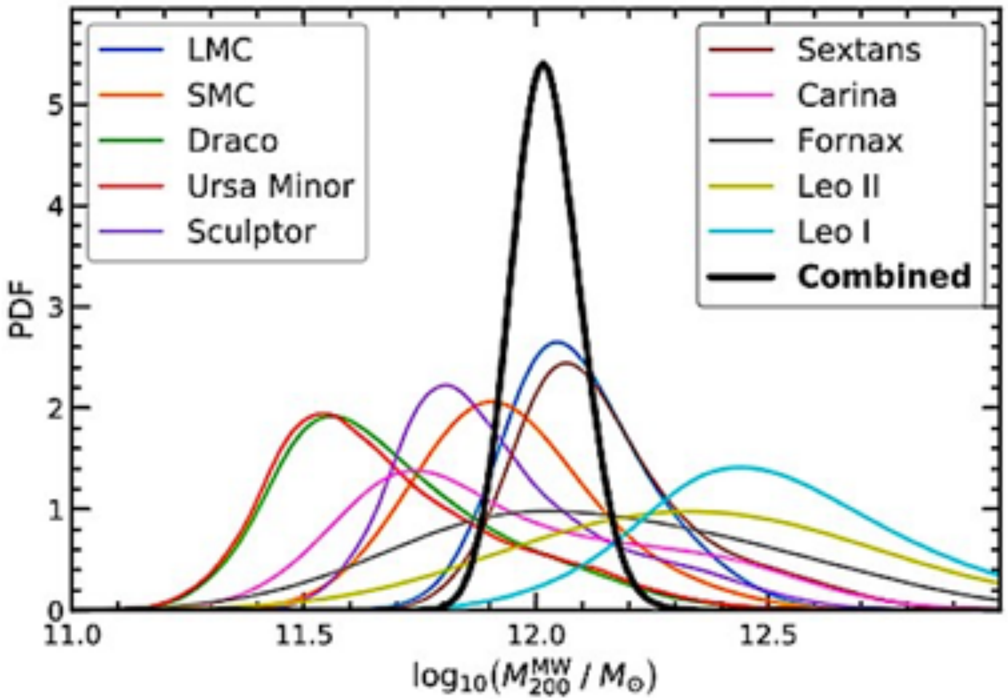


Fig. 2: The authors found the mass of the Milky Way to be about 1 trillion (10^{12}) times the mass of the sun. Each of the colored lines shows the value determined based on the orbit of a single satellite galaxy. The black line shows the combined measurement. Adding even more satellite galaxies to the calculation would improve the measurement even more. (Source: Figure 5 in the original Callingham et al. paper.)

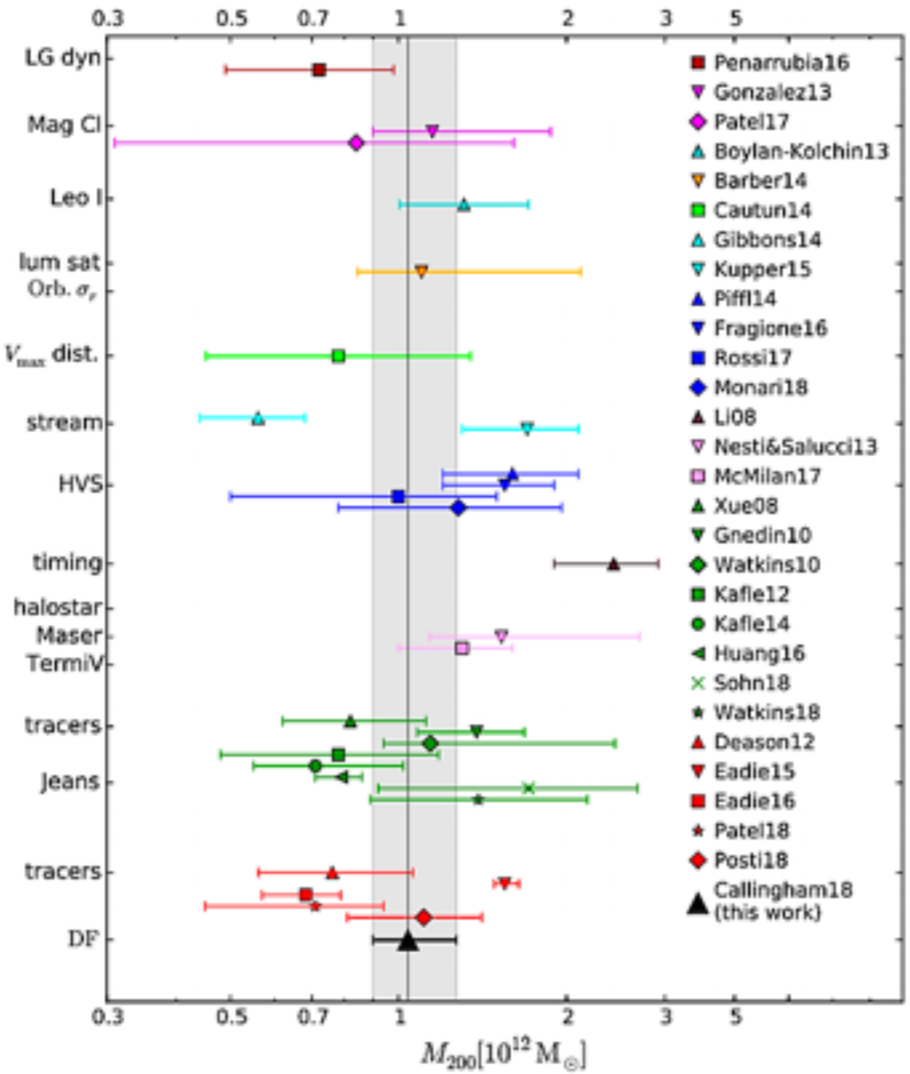


Fig. 3. A comparison between the measurement of the mass of the Milky Way in today's paper (black triangle) and previous measurements. This figure illustrates the range of values and the uncertainty of each measurement. The error bars on the measurement in today's paper are much smaller than those of many previous measurements. (*Source:* Figure 7 in the Callingham et al. paper.)

• Applying our method to ten classical MW satellites gives an estimate for the total mass of the MW halo of $M_{200}^{\mathrm{MW}} = 1.04^{+0.23}_{-0.14} \times 10^{12} M_\odot$. This result agrees well with most previous estimates in the literature but with a rigorously tested accuracy (~20%) which is better than most other estimates.

• Combining our total DM halo mass estimate with recent estimates of the halo mass within 20 kpc we infer a concentration for the MW halo of $C = 12.0^{+3.5}_{-2.3}$. This is higher than predicted by the EAGLE simulations, which include the contraction of the halo due to the formation of the galaxy at the centre. EAGLE haloes with masses of $10^{12} M_\odot$ have a median concentration of 8.2, with only ~3% of them having concentrations of 12 or higher. However, while this suggests that the MW is an outlier, the inferred MW halo concentration has large uncertainties, and the true value could potentially be lower and in better agreement with the EAGLE haloes.

• Our halo mass estimate can be improved by increasing the number of halo tracers and/or reducing the observational uncertainties. We found that the observed proper motions of the ten classical satellites are already so precise that further improvement will make little difference to the halo mass estimate. Increasing the number of satellites, on the other hand, for example by including the ~50 currently known satellites in the MW, would reduce the mass errors to ~14%. Further improvements would be possible by analysing all ~125 satellites that are predicted to reside in the MW (Newton et al. 2018), which would result in a ~10% mass uncertainty, a factor of two improvement over our current estimate.

Source: This article first appeared in *astrobites* 10 September 2018.

Don't underestimate the undergrads!

V-Band Photometry in V404 Cygni

Cormac Larkin
University College Cork

V404 Cygni is a low-mass X-ray binary in the constellation Cygnus. The two stars comprising this system are an accretor (a black hole candidate or neutron star) and a donor star (a low-mass late type star). The accretor grows by accumulating matter from the donor star. Periodic outbursts of X-rays occur as mass is transferred from the donor to the accretor. It underwent a period of outburst this summer, beginning on June 15th 2015. I performed V band photometry on the system in August to attempt to ascertain whether the system had returned to quiescence or not. I used the McDonald 1m telescope in Texas, owned and operated by *Las Cumbres Observatory Global Telescope Network.* My observation time was awarded to me by the *Faulkes Telescope Network*. Using the Aperture Photometry Tool, I found the V magnitude on August 12th to be 17.24, which was lower (and thus brighter) than the quiescent V magnitude averaging 18.3-18.4 but higher (and thus dimmer) than the peak V magnitude of 12.1. From the data I obtained, the system appeared to be still active, but was dimmer than when at peak activity. From this, I inferred that activity in V404 Cygni was dissipating but not yet returned to quiescent levels. This work was presented in poster format at both the Irish National Astronomy Meeting 2015 and at the Young Scientists Journal Conference 2015, where it came in 3rd place overall.

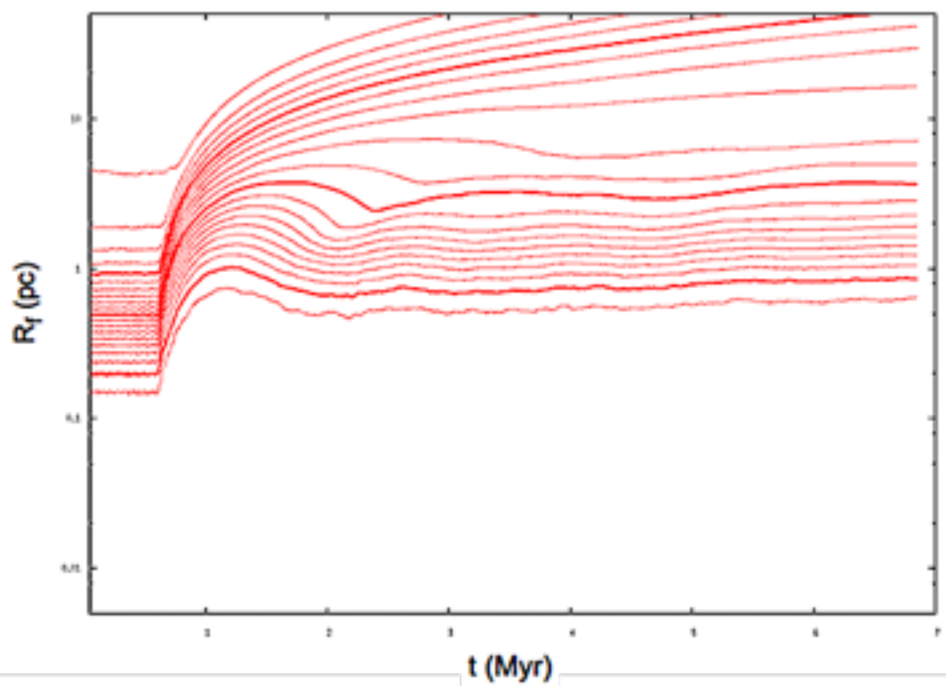
The combined 5×60 second image used to measure the magnitude of V404 Cygni. Image acquired using the 2 metre *Faulkes Telescope South* instrument via Las Cumbres.

Cormac is entering his final year of high school in Cork, in the south of Ireland. Last summer he completed an internship in the physics department at University College Cork, where he worked on the following research project. Cormac is now the Managing Editor of the Young Scientists Journal and a Research Collaborator with Armagh Observatory working on data mining in the Small Magellanic Cloud in the search for new O-stars.

N-body sims of the Dynamical Evolution of Young Star Clusters

Bhawna Motwani
Indian Institute of Technology Roorkee, Uttarakhand, India

A much-debated classical scenario of star-cluster formation, first delineated by Hill (1980), suggests that the collapse of a proto-stellar core within a parent molecular gas cloud gives rise to an infant gas-embedded cluster. Subsequently, the residual gas is driven out of the cluster by kinetic feedback from stellar winds and radiation, which dilutes the gravitational cluster potential and leads to core collapse. However, pertaining to a star-formation efficiency ε <50% (Kroupa 2008) and slow gas-expulsion, the cluster remains fractionally bound and ultimately regains dynamical equilibrium. With the help of NBODY6 algorithm (Aarseth 1999), we perform N-body simulations to examine the time-evolution of confinement radii (R_f) for various mass-fractions *f* of such emerging clusters. From this, we infer the cluster re-virialization times (τ_{vir}) and bound-mass fractions for a range of initial cluster-mass and half-mass radii. We relate the above properties to stellar evolution and initial mass segregation in the simulation and find that primordially segregated systems virialize faster and possess a lower bound-mass fraction on account of mass loss from heavy stars and 2-body+3-body interactions whereas, stellar evolution does not exhibit significant effect. This research is the first instance where a realistic IMF (Kroupa 2001) has been utilized to perform an extended parameter scan for an N-body cluster model.



Lagrange radii evolution profile for a computed *N*-body model with initial mass = 3^4 $M_\odot$ and half-mass radius = 0.5 pc. From bottom to top, the curves represent mass fractions from 5% to 99% in steps of 5%. The delay time time after which gas-expulsion starts is 0.6 Myr.

Bhawna Motwani conducted this N-body study as a part of her summer research Prof. Pavel Kroupa and Dr. Sambaran Banerjee at the Argelander Institut für Astronomie, Bonn, Germany.

Why MeerKAT – and astronomy – matter

A big moment for Africa

Vanessa McBride

Astronomy in Africa will take a giant leap forward with the unveiling of the 64-dish MeerKAT array in South Africa on July 13. The MeerKAT will be the largest and most sensitive radio telescope in the southern hemisphere until the Square Kilometre Array (SKA) is completed.

Why is this such a big deal? After all, Africa has many challenges more pressing than exploring the universe. But, as my colleagues and I recently argued *in an article for Nature Astronomy*, astronomy occupies a special place among the many efforts to address development challenges. It has a unique ability to stimulate thoughts of "what is possible" in the minds of marginalised communities, women and children.

Astronomy connects philosophical, cultural and inspirational elements with the cutting edge of science and technology. This affords the discipline a unique advantage to foster socioeconomic development. For instance, astronomy has been used in *Sierra Leone* to improve middle school pupils' literacy. It worked because they loved what they were learning.

Astronomy techniques are also used across sectors from *conservation* to *medical imaging*.

The *International Astronomical Union's Office of Astronomy for Development* uses astronomy to drive positive developmental change. It has ten regional and language centres. Three are in Africa, in Ethiopia, Nigeria and Zambia. The global coordinating office is situated in South Africa.

Our challenge as astronomers is not only to grow the discipline in Africa. We also need to ensure that this growth is accompanied by the educational, technology transfer and societal engagement initiatives that can drive the continent's development priorities.

Skills training

The funding we disburse has been used to run a number of programmes aimed at developing skills among school and university students.

One of these was the *Madagascar Astronomy Python Workshop in 2017*. It focused on practical coding in the Python programming language for university students and lecturers. The aim was to build on astronomy tools that participants can develop for their own research and teaching, not necessarily in the field of astronomy.

At school level the *Girls Astronomy Camp* was held in Abuja, Nigeria earlier this year. (See following article.) This not only dealt with education. It also tackled the large gender disparity in science, technology, engineering and maths fields, which can be a complex, socio-cultural issue in many regions.

It's crucial for educational interventions to address the fact that astronomy students often find employment outside the field. Students must learn science in a way that allows them to build their repertoire of transferable skills.

So the Office of Astronomy for Development has funded a number of Joint Exchange Development Initiative workshops in *Namibia*, *Mozambique*, and *Mauritius*. These workshops focus on direct transfer of specific skills in an informal but intense learning environment. They're also excellent for data science skills, which are particularly important for economic growth and jobs

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Vanessa McBride is an astronomer with the International Astronomical Union's Office of Astronomy for Development. This article first appeared in The Conversation July 12, 2018. An earlier version of this piece appeared in Nature Astronomy and was co-authored by Ramasamy Venugopal, Munira Hoosain, Tawanda Chingozha & Kevin Govender.

Beyond disciplinary boundaries

Astronomy can also be put to use in perhaps surprising ways to boost development.

One of our projects, *Accessible Citizen Science for the Developing World*, has married health issues with astronomy skills through running a proof-of-concept type intervention. Retinal defects are common, but curable. *Peek Vision*, a social enterprise that works to bring better vision and health to everyone, developed a retinal imaging device that can be easily used, even in rural Kenya, with an Android phone.

But there weren't enough qualified ophthalmologists at hand to use the app to diagnose retinal problems. So Peek Vision teamed up with astronomers at a citizen science portal called the *Zooniverse*. In the same way that the citizen scientists had previously worked to classify thousands of galaxies, they were called on to learn how to identify retinal problems on the Zooniverse portal.

Such partnerships are quintessential examples of working together across disciplinary boundaries to achieve development outcomes.

Creating spaces

There are numerous other initiatives that contribute to development through astronomy. Large astronomical infrastructure investments like MeerKAT aim to stimulate the technology industry and advance the development of technical skills.

International aid initiatives with a science focus like *Development in Africa with Radio Astronomy* (DARA) and its sister project, *DARA Big Data*, are using the momentum generated through the SKA programme to develop skills and train more astronomy students for the continent.

Of course, the few examples illustrated in this article hardly begin to address the myriad challenges facing Africa and the world. Technology and science can only do so much: these challenges have solutions that are, at least in part, driven by human values.

That's why conversations that span natural and social sciences are key to making development progress on the continent. The Office of Astronomy for Development is one of the spaces hosting these conversations. We're challenging astronomers and other scientists to reach across the disciplinary boundaries to explore how their skills can help Africa meet its development goals.

It's their future.

2018 Girls Astronomers Camp, Abuja Nigeria

Onuche Henry Ogu

The Abuja Girls Astronomy Camp was held 28 April 2018 at Obasanjo Space Center Abuja. The event was planned and organized by Astronomers Without Borders. The Girls Astronomers Camp is a hands-on way for young women to learn about astronomy. The programme was packed with fun and educational activities.

The Girls camp is an OAD/IAU (Office of Astronomy for Development)/(International Astronomical Union) initiative, funded and supported by Astronomers Without Borders International (AWB), Universe Awareness (UNAWE), VIXEN Co. Ltd, National Institute for Astrophysics in Milan, Italy, and the National Space Research & Development Agency. The camp aims to change the gender lopsidedness in the school enrollment in other to bridge the gap that exists between male and female children enrollment—particularly across the northern part of Nigeria. We aim to reach thousands of school girls as we carry out these camps in the different states across Nigeria.

The April 2018 camp started at noon with Registration and Red Carpet/ interview sessions with the girls and accompanying guests. The National Coordinator of AWB Nigeria, Mrs. Olayinka Fagbemiro delivered an introductory address. Dr. Francis Chizea who represented the Director General of NASRDA gave a remark highlighting the importance of the event.

The event moved on in earnest with career talk. Engr. Yewande Adeyeye spoke on the 'History of Women in Space Science & Technology.'

A tea break followed by an introduction to solar glasses. The girls were excited that they could look at the Sun without getting hurt. The next agenda of the camp was a STEM Quiz which comprised 20 objective questions spread across Astronomy, Mathematics, Science, and Physics.

After the Quiz, the girls had lunch. The Chair of e-Worldwide Limited, Dr. Salma Abbasi delivered the talk. She is a Technologist, Philanthropist and Social activist with over 30 years n the field of technology and business. The subject of her talk was the importance of STEM. She encouraged the girls to develop interest in STEM courses and emphasized on the importance of their involvement in Science & Technology.

Hands on Activities followed the Pep Talk. There was a variety of activities in this session. The girls were put into different group to build a prototype of a Communication Satellite, Tinkering (using DC motors and Markers), Universe in a Box, Coupling a Galileoscope, Solar system modelling and the youngest girls made Paper Satellites. The session was very engaging as the Girls learnt something interesting.

Afterwards, the girls watched a movie called 'Hidden Figures' which depicted Girls involvement in STEM and Astronomy. Star gazing session & Barbecue ended the activities for the day. They had the opportunity to look at Venus and the Moon as they were the brightest on our horizon.

We at AWBNigeria would like to use this opportunity to thank all our Sponsors and Contributors for making this dream a reality. We remain committed to spreading Astronomy throughout Nigeria.

Onuche Henry Ogu is a Research Engineer with the National Space Research & Development Agency and part of the project team of Astronomers without Borders Nigeria.


A galaxy is music we can see. It is so faint it is almost not there, yet it yields such an incomparable strength that its beauty alone is enough to keep us looking.

Why do galaxies make central bars?

Douglas Bullis

Galaxies are so luminous it is easy to think of them as mass that shines. But what happens if we consider galaxies not as mass that shines but as energies that don't shine — momentum, inertia, heat, magnetism, torsion, shear, absorption, even the dark energy about which we know little beyond that it certainly doesn't shine?

From the opening image above, it may seem that barred galaxies are galactic astronomy's messiest housekeepers. If we consider a galaxy only as mass that shines, the statement is true. Imagine that you have booked a holiday rental based on all those beautiful images of grand-design spirals, so tidy, pretty, and orderly. Then you arrive and you find you're in a barred spiral. You can hear your wife's response even now: "Just *look* at this place, will you! It's a fright! We want our money back."

This would probably be a poor time to inform your wife that a barred spiral galaxy is astronomy's most glorious embodiment of energy that doesn't shine: "The chaos of a barred galaxy's arm-bar connection is an exquisite fuel pump that keeps the galaxy from running out of gas", or "All those beautiful starry dust bunnies in the far outskirts get their energy from that bulgy, squishy thing in the middle."

A useful analog of heat capacity is trying to push a balloon to the bottom of a swimming pool versus letting it rise to the top. It takes your energy input to push it down, but rises to the top by itself if you simply let go.

One must concede that this may not be the best way to endear your star gazing hobby to the person who wishes you would get to bed at a more reasonable hour on those long nights when there's no moon.

You can always give astronomical conventions a literary spin by pointing out that barred galaxies are a Shakespearean drama with a huge cast of exotic characters, many acts, and a multitude of scene changes. In the end the protagonist commits suicide (several times), half the characters have met violent ends and the other half have lost their personalities. All this as the once brilliant stage lights dim into cimmerian night.

If you fancy the dramatic you can try, "The play is about the multi-billion-year life span of the bar in our Milky Way galaxy. It has a remarkable cast of characters: Mass-Luminosity, Tully-Fisher, Age-Metallicity, Spectral Energy plus walk-on parts for [Fe/H], [Na/O], [Ti/O], [Ba/Eu], and cosmic rays."

You needn't tell me your wife's response to this: I'm married, too.

So let's skip the casting call and introduce two unknown hopefuls to see what they can do: *Negative Specific Heat* and *Angular Momentum Transfer*.

And who are they? *Heat* is the energy arising from the random motion (kinetic energy or *E*) of the particles in a given volume. *Temperature T* is the amount of heat present in an object, expressed in a defined scale. In our play the scale is Kelvin, or K. Zero K is –273.15 Centigrade.

Specific heat is the heat required to raise the temperature of a given mass of a substance by a specific amount. *Negative specific heat* happens when gravitationally-bound systems gain kinetic energy as they lose total energy. A steaming cup of coffee is an example of negative specific heat. The liquid contracts (cools) as the kinetic energy of steam (heat) is lost to the surroundings. When main-sequence stars radiate energy into space, they contract to maintain their heat balance; they retain the same average kinetic energy, but in a smaller volume. As a satellite orbiting Earth slows down from atmospheric friction it moves to a lower orbit and higher kinetic energy (velocity). As a star cluster in equilibrium with its surroundings radiates kinetic energy away as light, the cluster loses heat capacity and therefore contracts. Gravity pulls the more massive stars closer to the centre while the lightweight stars out on the edges lose energy and escape or "evaporate" into the galaxy as field stars. The more familiar term used for this is "core collapse".

Negative heat capacity is the amount of energy a system requires to remain in its most tightly bound state. Galaxies are the most complex example of what happens to a system with negative heat capacity. Galaxies evolve toward the most tightly-bound configuration their mass and energy permit them. Elliptical galaxies arrive at this state when the combined orbital velocities of all their stars provides enough kinetic energy to balance the inward force of gravity. Spiral galaxies do it by rotating.

Spiral galaxy arms are triple-schizophrenics: their dense stars rotate in one manner; their light, loose gas clouds rotate in another; and their heavier dust clouds rotate in a manner different from either. None of these move in tidy perfect circles around the galactic centre. They wobble up-and-down, in-and-out, fore-and aft with respect to a perfect circle. The motion of a given volume of stars, dust, and gas is more accurately characterised as a marble rolling inside a hula hoop which itself wobbles irregularly around the galaxy centre. The combined motions of everything in the volume set the diameter of the marble at any given point. The more correct term is that the hula hoop is an inertial frame and the marble moves in a tiny volume along a guiding centre in the tube.

The lamentable fact for galaxies is that they will never achieve dynamic (thermal) equilibrium. Their stars lose energy via radiation. Their huge gas clouds collapse into myriad tiny stars. Gas and ions lose energy as they convert their motion into magnetohydrodynamic shocks. Friction robs energy from gas clouds as they brush past each other. Magnetic fields dissipate energy as they dampen out shock waves. Rotational, vibrational, and electronic transitions convert molecular energies into photons. All these increase negative heat capacity.

Galaxies respond by spreading out. The name of the process that carries this energy is *angular momentum transfer*.

How cats and galaxies steal from each other's food dishes

Stars and gas in galaxies are like two sibling cats. They cozily sleep next to each other. When they wake up they steal from each other's food dishes. They hiss. They yowl. Fur flies. Then time for a nap.

Put a little more formally, within a gravitationally bound system the total amount of momentum remains constant. It is neither created nor destroyed, but it can be transferred (i.e., from cat to cat) by specific heat (cat food). The visual evidence of the heat transfer is momentum (flying fur). The aural evidence is hisses and yowls, which galaxies call "star formation." Momentum transfer explains phenomenon as diverse as:

- why red giants expand and then contract
- why AGB stars turn into planetary nebula
- why a threesome of stars in a cluster will hurl the smallest one completely out of the cluster and then settle down as a more tightly bound pair closer to the middle of the cluster
- why star cluster halo stars evaporate away while their centre stars grow tighter
- why massive Jupiters clear out debris discs between themselves and their star
- why galaxy bulges start out tiny and get big while the stars in the spiral arms drift outward above and below the disc plane
- why spiral bars come and go without destroying the galaxy disc
- why dwarf galaxies are preferentially arranged in polar or equatorial planes of their host galaxies
- why galaxy poles preferentially align along the direction of incoming gas flow along cosmic filaments

Momentum is the product of the mass m and velocity v of an object; it is a linear vector. *Angular momentum* is the circular equivalent of linear momentum. Linear momentum is the vector of your car going along a straight road. Angular momentum is the vector of your car going around a curve. On earth the relation between negative specific heat and angular momentum transfer is readily seen in satellite videos of hurricanes. As the sea adds heat to the wind, the kinetic momentum has to go somewhere. Satellite videos show the outer regions of the hurricane fanning outward from the edges even as the arms are spinning inward toward the hurricane's "eye". *1*, 2, *3*. But where — and why — does incoiling energy stop and transfer into outward spreading?

In galaxies excess angular momentum accumulating in the core rises into the low-density inner halo above the bulge, then spreads outward across the disc into the distant spiral waves beyond the galaxy's co-rotation circle (*Fig. 9 below*). While hurricane arms visibly spread away at the edges, galaxies don't spread their momentum outward so dramatically because dark matter constrains disc spreading. Instead, the gas initiates star formation in the outer disc. That is why we find bright young star clusters quite far out into the spiral outskirts, which is a regime dominated by atomic rather than molecular hydrogen.

Where do stars go in galaxies?

Stars and gas clouds rotate around their galaxy centres rather more erratically than our schoolbook texts told us. Galaxy discs liken somewhat to an old 33 rpm record left in the sun too long. Galaxy discs are thicker and not rigid, yet they can still warp from excessive heat. Their stars behave like tiny beads on a lumpy surface that is constantly shifting beneath them. They wobble (a) up and down vertically, (b) in and out radially toward the centre of the galaxy, and (c) fore and aft along the tangent line of their rotation. The stars in an arbitrary volume, say a sphere 1 kpc (3260 ly) in diameter, behave more like a swarm of bees buzzing every which way inside a swarm as the entire swarm itself heads *en-masse* toward its destination.

"Self-gravitating systems evolve toward the most tightly bound configuration that is reachable via the evolution processes that are available to them. They do this by spreading – the inner parts shrink while the outer parts expand – provided that some physical process efficiently transports energy or angular momentum outward. The reason is that self-gravitating systems have negative specific heats. As a result, the evolution of stars, star clusters, protostellar and protoplanetary disks, black hole accretion disks and galaxy disks are fundamentally similar. How evolution proceeds then depends on the evolution processes that are available to each kind of self-gravitating system." (John Kormendy, *Secular Evolution in Disc Galaxies*, Canary Islands Winter School, 2013)

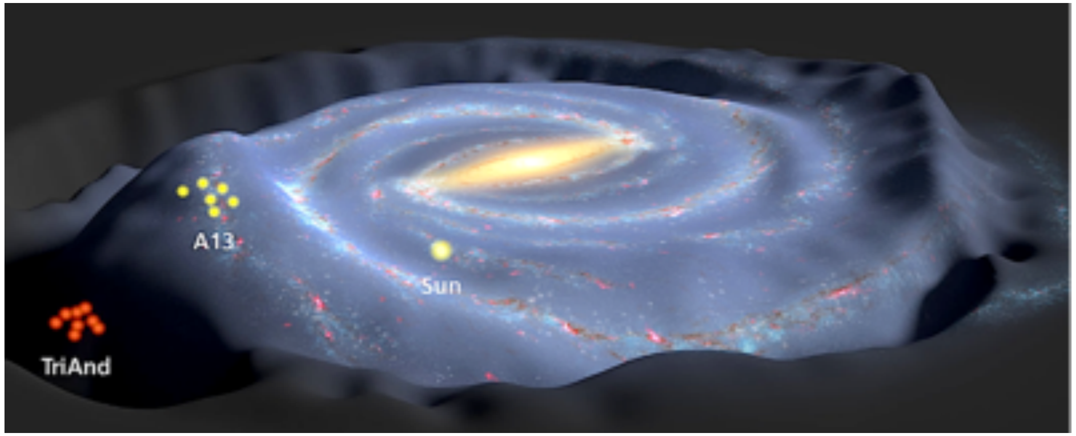


Fig. 1: Earlier this year *Bergemann et al 2018* studied two groups of stars in the outer Perseus Arm very far apart from each other yet exhibited identical spectra. Both star sets exhibited nearly identical metallicity, age, size, and velocity. There was a high probability that they originated in the same molecular cloud collapse but were separated across thousands of light years by a large warp in the Perseus outer arm. The warp resulted when a smaller but still quite massive galaxy punched through the outer MW disc billions of years ago. The interloper was eventually absorbed into the Milky Way., but the event so disrupted the disc that stars born in the region millions of years ago exhibit triaxial (3-D) velocity components that differ significantly from young stars born in the same area.

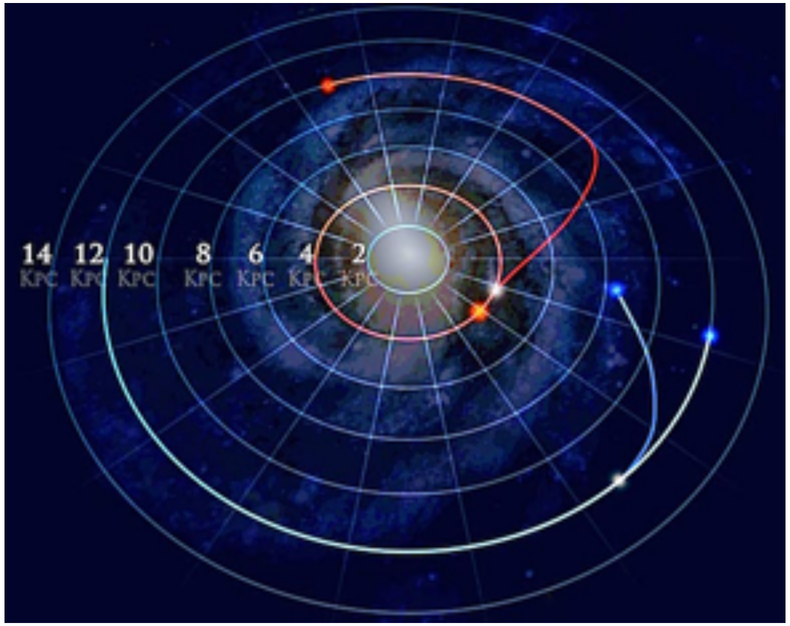


Fig. 2: A wandering star can move a long way in several billion years. *Michael Hayden et al* 2015 found that up to 30% of chemically mappable red giants originated in locations far from their current homes. Some of their migrations originated when massive binary stars ejected a smaller interloper (the 4 kpc ejected star above). Other stars were disrupted by massive giant molecular clouds in or passing through the Galactic disc (the 12 kpc star above). At up to 10 million $M_{\odot}$, molecular clouds are the most disruptive objects in a galaxy disc.

Stellar migrations in and through a galaxy disc are complex and at times nearly inchoate. At the solar radius a star takes about 230 million years to make a circuit at a forward orbital speed of around 220 km s^{-1}. Yet at the same time our Sun's orbit oscillates 200 pc above and below the disc every ~64 million years. The Sun also wobbles in and out radially toward and away from the Galactic centre every ~150 million years. Each of these motions is epicyclic. Merged into a common vector they become an eigenvector in a given sample volume filled with other stars each part of its own vector set. The main cause of the constant disruptions of stellar vectors around a galaxy is the scattering effect of giant molecular clouds, star cluster relaxation, and supernovae shock fronts.

The Sun circles the Galaxy in a wobbly path that continually changes in response to the large, irregular mass concentrations that pervade a galactic disc. The Sun is currently about 8.5 kpc from the Galactic centre and about 20 pc above (north) of the Galactic plane. It is moving radially inwards toward the core at 10 km s^{-1}, tangentially forward at ~5 km s^{-1} faster than the average star at this radius from the Galactic centre, and about 7 km s^{-1} vertically from the the Galactic plane. In a side view it would look like an eccentric ellipse with a very large precession (Fig. 4 opposite).

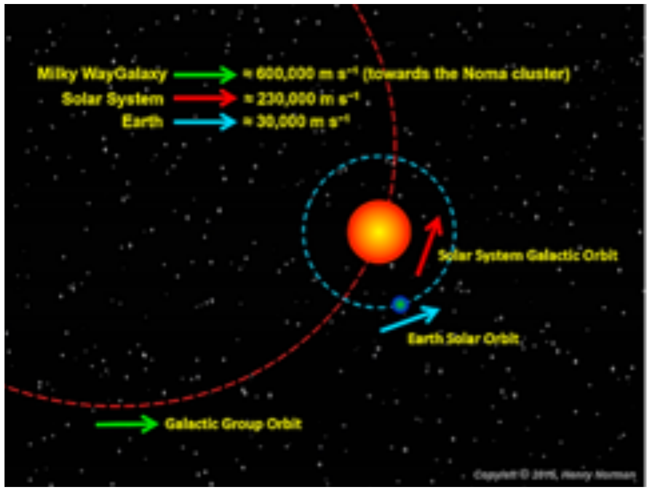


Fig. 3: The presence of spiral arms, the Galactic bar, and the clumpy presence of giant molecular clouds significantly perturb the Sun's orbit around the Galactic disc. Predicting the location of the Sun in the disc is a value in a Poisson distribution (probability function) that is stable for only a short time.

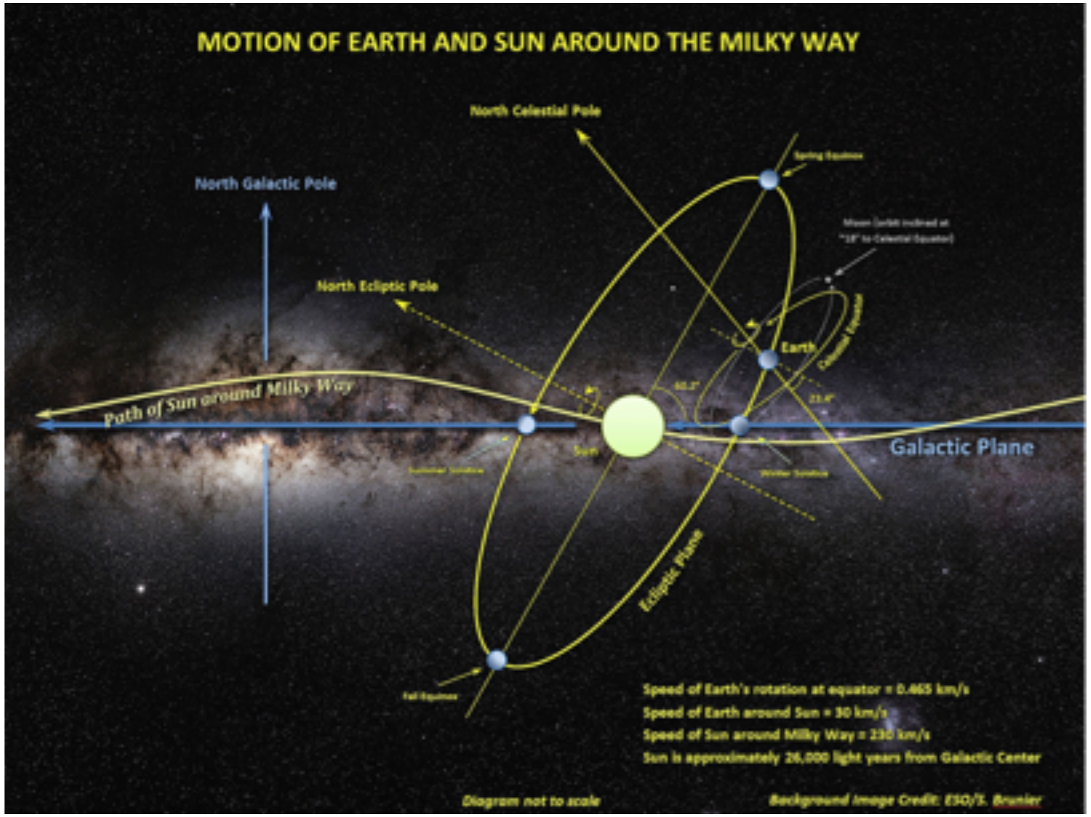


Fig. 4: A star has three ranges of motion (epicycles) as it rotates around a galaxy: up and down, side-to-side, and fore and aft along the vector of its forward path. The Sun's main deviation from a true circle around the disc is up and down. That motion was likely imparted by the gravitational fields of massive molecular clouds which the Sun has encountered during its ±17 orbits around the Galaxy. The Solar System traces out a three-phase (triaxial) sinusoidal path in its orbit around the Galactic centre. Using Galactic North as the inertial frame of reference, the Earth and Moon rotate counterclockwise. The Earth likewise revolves *counter*clockwise around the Sun. The Sun and its satellites in turn revolve contrarily *CLOCKWISE* around the Milky Way.

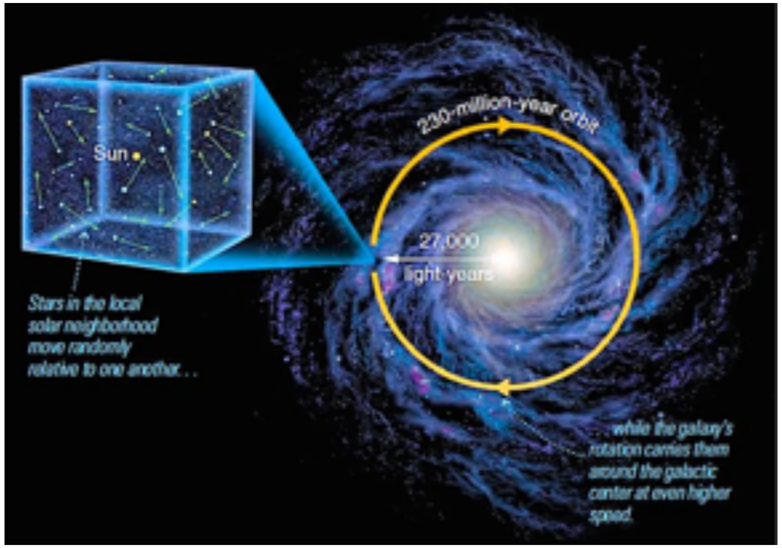


Fig. 5: Using the bee-swarm analogy, a 10 pc parcel of stars centred on the Sun rotates around the galaxy in a near-circle, but the stars within each parcel have their own significant peculiar motion in relation to the others. The most significant perturbation on a parcel will be its transit through a spiral wave. Low-mass clusters are scattered during an arm crossing.

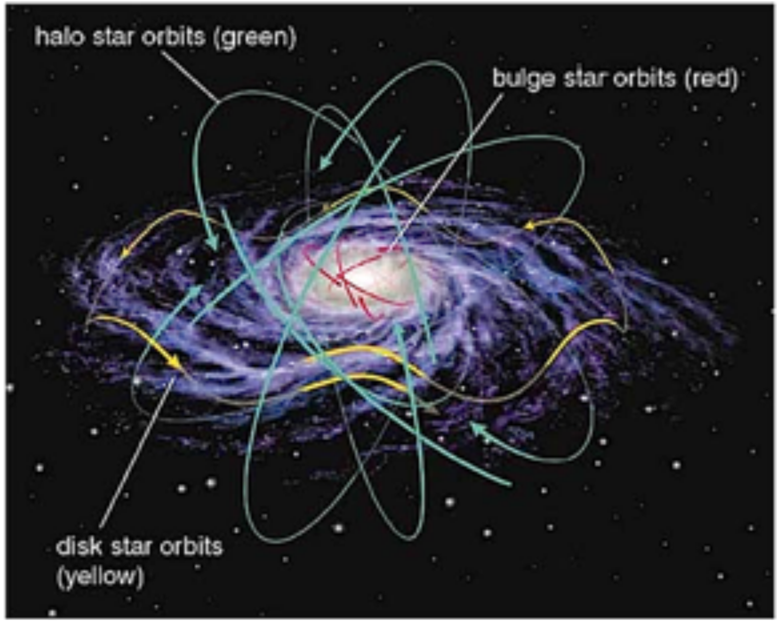


Fig. 6: Disc galaxies have three major families of stellar orbits around the centre. Bulge stars rotate in quasi-ellipses that are constantly rearranged by the stars swirling around them. Globular clusters and elliptical galaxies share this life of orbital inconstancy. Disc stars are described in more detail in the text. Halo star orbits are large, slow, and near-circular.

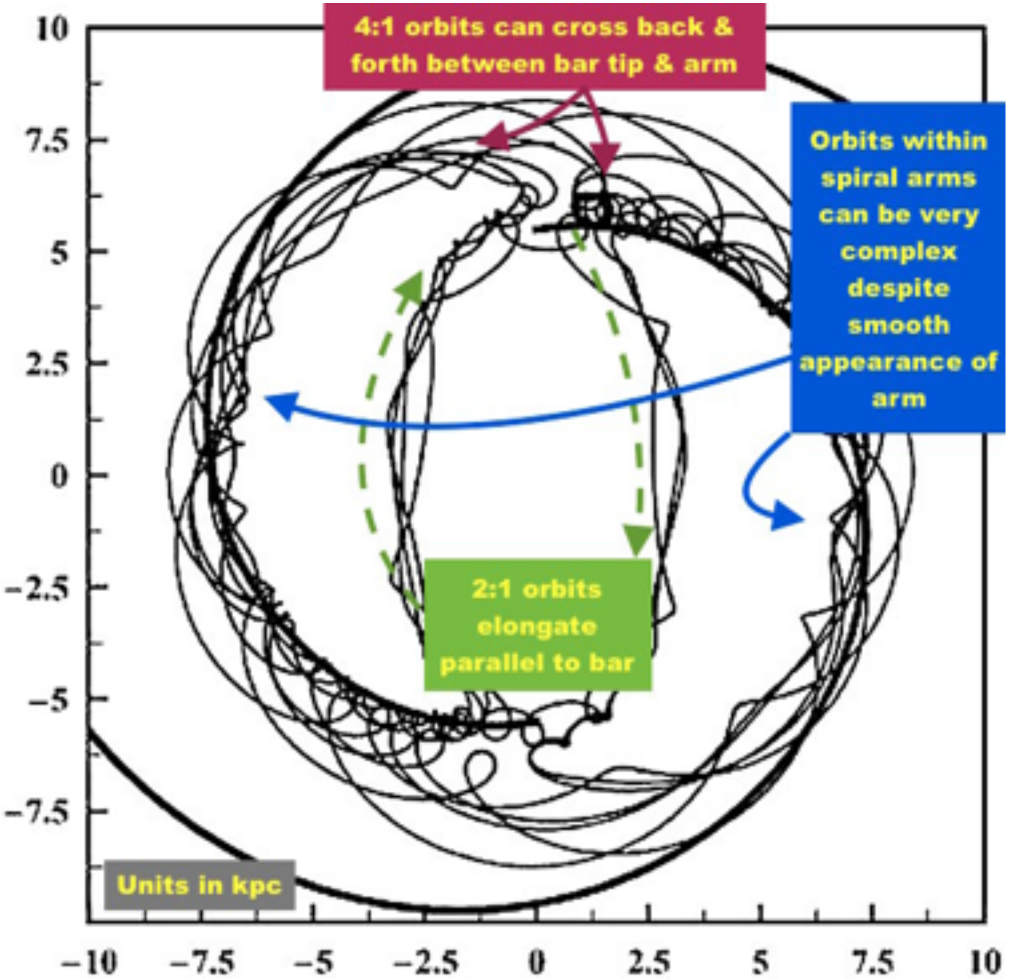


Fig. 7: Variations of peculiar orbits in a sample of six stars rotating around a barred galaxy. The lines here show star paths along their guiding centres, not the rotation of the entire ensemble around the galactic centre. This orbital plot traces a central bar extending into a spiral arm in the early stages of the bar's evolution. Even projected on this simple 2-D surface, the paths are so disorderly as to defy description. Considerable crosstalk occurs between adjacent galactic arms and the newly developing bar at the bar ends. Dispersion initiated during molecular cloud interactions becomes inchoate from bar-arm stellar and cloud mass interactions.

How galaxies invented the traffic jam

There you are, happily hurtling down galactic life's multi-lane highway. Lots of traffic today, dammit. From a bridge overpass, a dawdling onlooker sees you and all the other cars moving in the same direction and at the same velocity. A few irregularities are observed as cars overtake and pass someone in the slow lane, but these do not disrupt the overall flow. The onlooker doesn't notice subtle changes like a driver wandering slightly off the centre line of a particular traffic lane because those, too, don't disrupt the overall smooth flow.

The view is dramatically different from inside a car moving in this traffic. The driver is on a co-moving platform which includes all the other cars nearby, all moving forward as a unit — the 2-D version of the co-moving bee swarm mentioned above.

To these drivers even quite small differences in the relative velocities of nearby cars are quickly spotted. A driver traveling at 100 km/h will notice "peculiar velocities" as small as 0.5 or 1 km/h. Exceed a driver's caution threshold and the brake lights go on. Once a single car's brake lights go on, so do others. That prompts even more drivers to do the same. The brake-light wave becomes self-reinforcing. Before we know it, we are in a traffic jam.

The overpass-bound observer might well miss all this because casual observers do not have a built-in time-lapse and instant-replay function. But if that observer was filming the traffic below, fast-forwarding the film later instantly reveals the development of a classic wave pattern.

The first brake light to go on initiates a sudden, if small, perturbation in the system flow. When the cars behind put on their brakes, the perturbation propagates logarithmically. Soon all the cars in view have compressed closer together and moving slower than before. The cars that were originally ahead of the perturbation zoom on into the distance, leaving a low-density zone ahead of the cars that first put on their brakes. Those cars see the way is now clear and speed up. The cars behind them follow, and so on back through the traffic jam, until the jam disappears. The distance between each car increases as they pick up speed, until the flow returns to its original density.

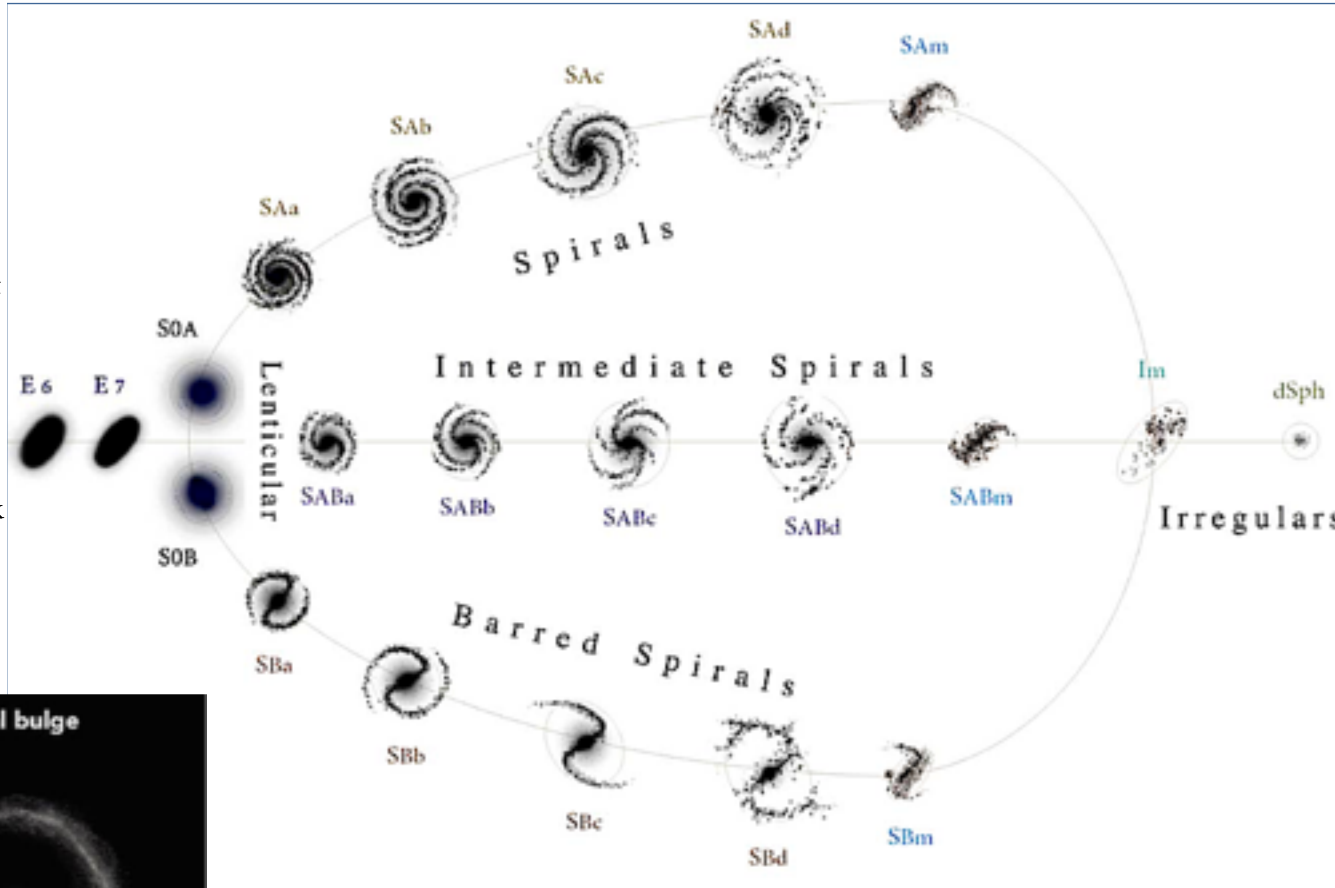
In all this, the most important phenomenon was the one neither the drivers not the onlooker noticed: as cars moved into the jam they slowed down, forming a wave crest. When they sped up and away, the entire wave crest moved *backwards.* The densest point in the wave originated ahead of the onlooker on the bridge but as the wave developed, the wave crest itself propagated *backward* through the oncoming traffic and now appears on the rear side of the bridge. The wave appears to pass through the traffic in the opposite direction the traffic is going, a phenomenon called the *perturbation precession rate.*

When stars encounter a spiral perturbation, the stars saw the wave, slowed down, and passed through it; it had no velocity of its own. As viewed by astronomers looking down from above, the star motions are relative to the wave's motion, which is relative to the observer's place and time, so to the observer the wave precesses away from its origin.

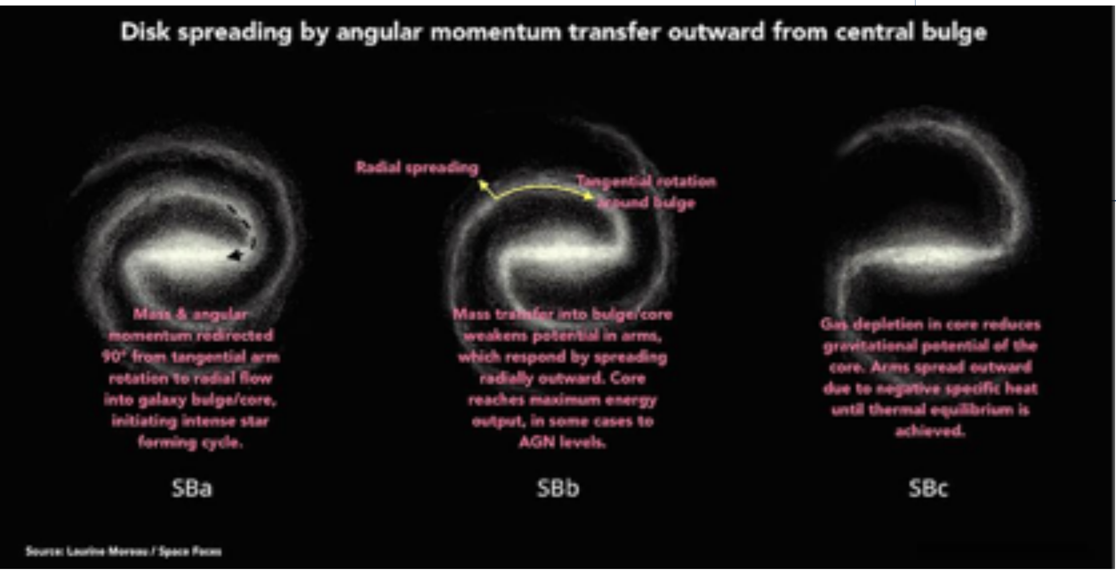
The original 1929 Hubble system provided the first ordering of galaxies that represented more than mere changes in optical appearance. In 1959 Gerárd de Vaucouleurs examined the central regions of galaxies and classified galaxies into strong bars, small or weak bars, and non-barred galaxies. He denoted non-barred spirals as SA, barred spirals as SB, and intermediate (weakly barred) galaxies as SAB.

A core with an inner ring would be classified with the subset term (*r*), core spiral (*s*), and combination (*rs*). de Vaucouleurs estimated the Milky Way's morphology type to be SB(rs)bc.

de Vaucouleurs also noted ring-like features in some galaxies, designating those as R or (R) – the latter being a pseudo-ring formed by tightly wound spiral arms. Rings form when a resonance between the orbital speeds of stars in the disk and a global pattern which transports stars and gas radially down the bar into the centre of the galaxy. Strong rings without a bar point to the bar itself having been dispersed into the ring.



Hubble – de Vaucouleurs Galaxy Morphology Diagram



Two years later, Allan Sandage published his own revised Hubble sequence as an atlas. As data accumulated for large numbers of galaxies, physical parameters for colour, HI content, concentration, surface brightness were devised so these varied properties could be cross-correlated. Today the sequence of morphology decodes complex information about the basic physics of galaxies.

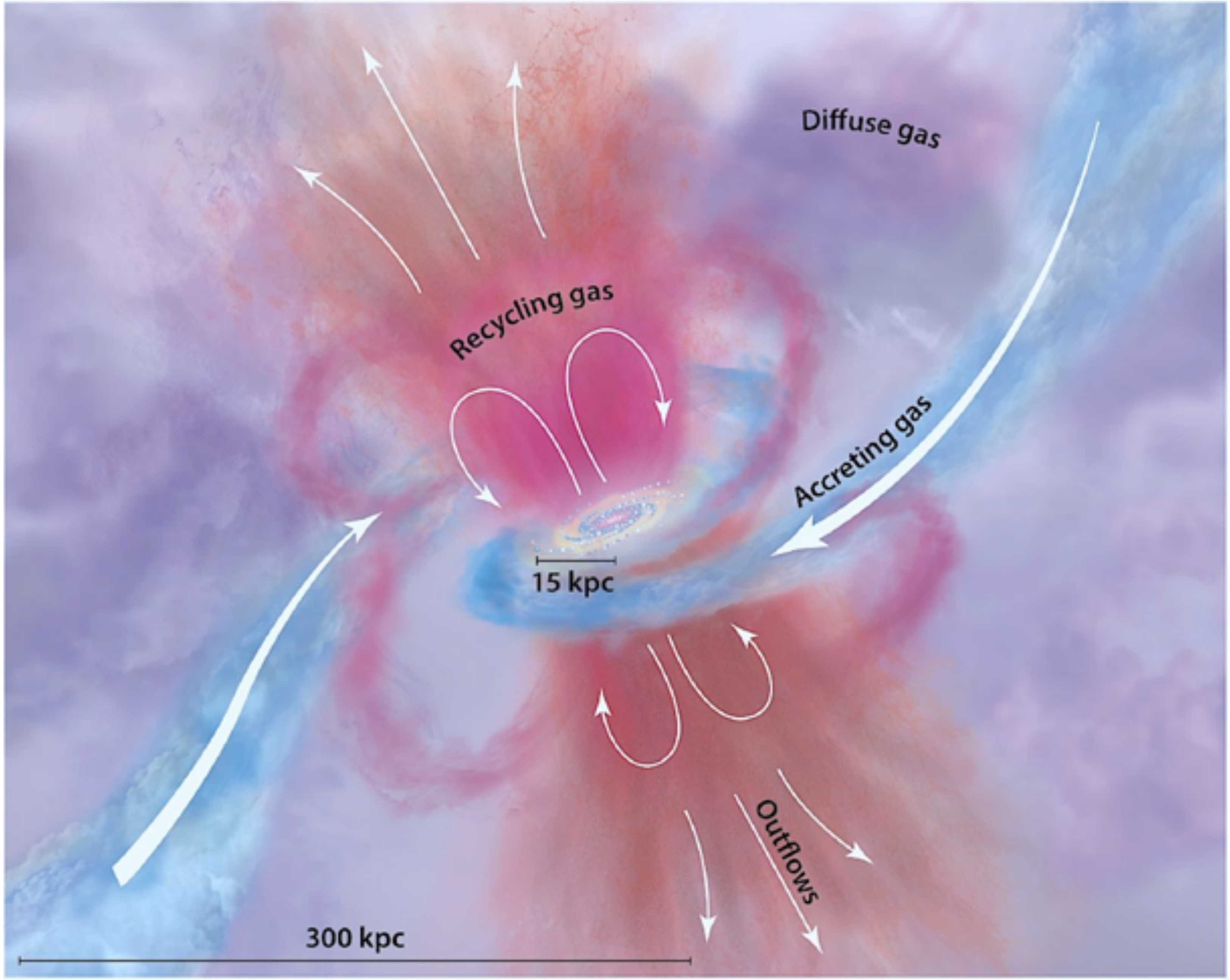


Fig. 8: A spiral galaxy's central bulge and gaseous disk is replensihed by filamentary accretion from the Intergalactic Medium (IGM). The filaments of the Cosmic Web (blue) comprise primordial hydrogen whose ultimate source is the emptying out of cosmic voids by what cosmologists sometimes call "negative gravity". That simply mans that continuously infalls along. Outflows of ejected gas from star-formation, supernovae, and central supermassive black holes are ejected from the disk at high velocity, while gas that was previously ejected is recycling. The Diffuse Gas halo shown here in shades of purple is composed of gas ejected by all these sources which is ejected with insufficient velocity to escape the galaxy. The gas rises as far from the disc as is velocity can carry, then gradually accelerates back down into the disc, where it will feed future star formation. The migratory pattern of gas ejection and later return infall return can take and mixed together over time.

Source: Tomlinson, Peeples, & Werk 2018: *The Circumgalactic Medium*. Annual Review of Astronomy and Astrophysics 2017. AA:1{46). *Astro-ph non-paywall here*.

A far back as 1964 Gerárd de Vaucouleurs suggested that our Galaxy might be a barred system. Eleven years later *Duus & Freeman* suggested that bars and inner rings are secular rearrangments of spiral arm disc matter. “Secular” means taking longer than a galaxy crossing time. At the time data was neither exact nor abundant enough to suggest that most spiral galaxies have been barred systems at least some time in their lives. The few unbarred galaxies that have never shown signs of bar activity are called bulgeless galaxies, e.g., M33, M63, and the “Fireworks Galaxy” NGC 6946.

Once conditions became energetically favourable for bars to form about 7 billion years ago, so many galaxies took advantage of the opportunity that 70% of galaxies visible to us today have bars of one kind or another. About 30% of these are visible only in the infrared due to dust in galactic discs. As is often the case, impressions based on visual observations are unreliable, a phenomenon called *selection bias*.

Barred galaxies are frequent visitors in astronomy magazines because of their visual appeal. But why do bars form and how do they evolve? For a quick primer, *watch this N-body sim* which portrays events across 7.5 Gyr.

Barred spirals were proportionately few until the universe was about half its present age, $z = 0.84$. In earlier epochs disks were either too dynamically hot or too low-mass to initiate the slow, quiescent evolution of bar formation.

Bars originate in a density perturbation radiating from the centre of the galaxy which squeezes the orbits of stars at the inner Lindblad resonance from circles into shallow ellipses.

An *Inner Lindblad resonance* (*ILR*) occurs where a star's orbital speed around the galactic centre is faster than the rotational speed of the spiral arm through which it is passing. This effect builds upon itself over time, bringing stars orbiting ever further from the ILR to elongate into self-reinforcing families of ellipses. To oversimplify a complex interaction of mechanics and pathways, bar stars shuttle across the bar twice for every circular rotation they make around the galaxy at their radius. Bars become stronger and longer in time while their rotation speed slows down. Bar rotation velocities are called *pattern speed* to distinguish from Grand Design *rotation velocity*. Spirals are known to alternate between barred and unbarred states in which bars self-destruct and reform as a result of their own over-acquisitiveness. The term “bar suicide” is used to describe galactic starvation, but a more colourful description is “galactic crash diet”.

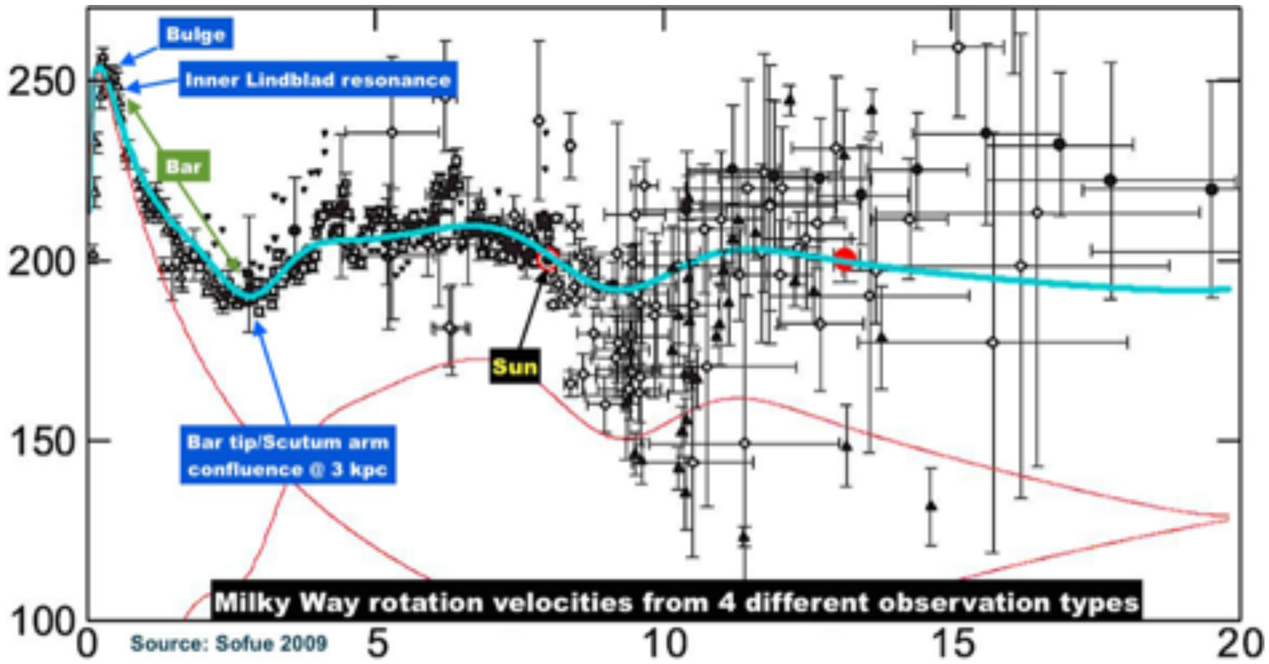
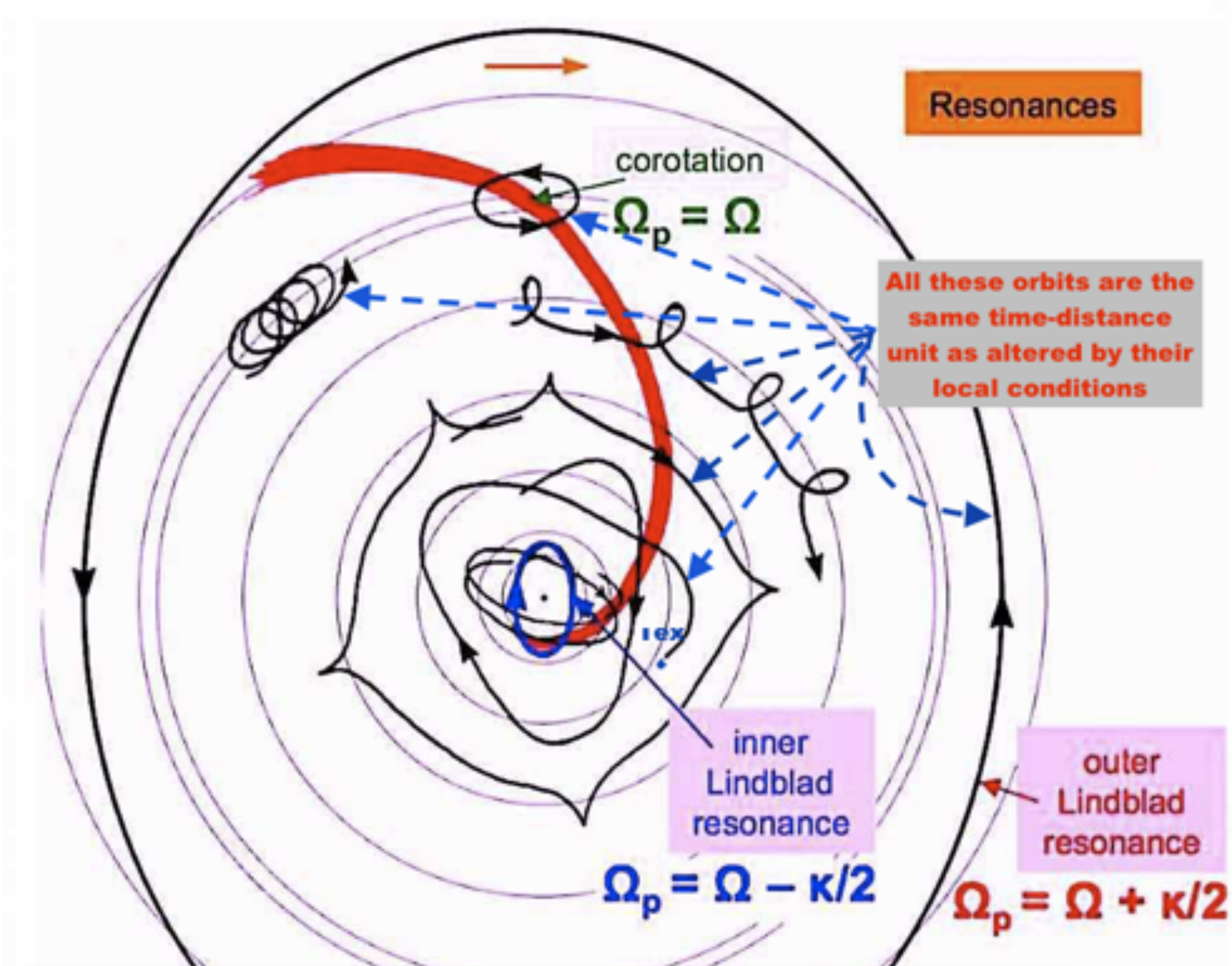


Fig. 9: Rotational velocities along Milky Way disc plane as presented in *Sofue 2009*. The rapid drop in rotational velocity between the Inner Lindblad Resonance and 3.5 kpc bar-arm confluence suggests a maturing bar whose rotational pattern speed is not yet uniform along its length. The large error bars beyond the Sun and co-rotation torus reflect uncertainties induced by source crowding, differential extinction, and small number statistics.

Fig. 10: Almost nowhere in a galaxy do disc stars travel in the tidy circles of coffee-table book renderings of the way galaxies work. As stars orbit a galaxy, they are bumped about by massive molecular clouds, close swing-bys past star clusters, near-misses with more massive stars or binaries. A star's ever-changing vectors move through many configurations over a single star's circumambulation around the disc. A velocity-position measurement today will be different the next time a measurement is made. At any one instant a group of stars in close proximity to each other, e.g. a 10 pc cube, have individual vectors that collectively resemble bees swarming in a co-moving ball. Over time individual orbits in a 10 pc cube mutually exchange energy with each other while also avoiding direct contact, rather like the N-body sims which depict them resemble gnat clouds in summer.

In the bulge stars travel in ellipses around the core as shown by the "standard unit" in the image caption. Just beyond, at the **Inner Lindblad Resonance (IRL)**, the standard unit stretches into two orbits around the disc plane. The galaxy's spiral wave rotates just once during that time, so the standard unit nutates into two lozenge shapes. Between the **IRL** and the **co-rotation radius** where the star orbits and spiral wave orbits are the same speed, the stars oscillate in and out and above and below the idealised circular path. The traces of their paths become various forms of gravity-constrained rosettes and loop-de-loops. At **co-rotation** the various triaxial eccentricities in a star's orbit gives it a path that looks like a succession of ellipses advancing forward slightly with each time unit. Beyond the **outer Lindblad Resonance (OLR)** the stars move in enormous ellipses that *appear* to travel in the opposite direction to the spiral wave. (They are not actually traveling backwards in the galaxy, only with respect to the spiral wave because the wave's rotation speed is faster than the stars'.) Stars' peculiar motions are more radically perturbed as they enter into and depart from a spiral density wave. S*ource: Kormendy 2013*. For more details about *Bertil Lindblad* see also *1*, *2*, *3*, *4*.



Orbital resonances of stars in spiral galaxies:
This diagram shows the variations of a single stellar orbit as the orbit is affected by the various resonances that exist in a spiral galaxy. All the black-arrowed orbital paths in the diagram are the same length and duration period as the standard time-distance unit of this black ellipse:

In the regions dominated by the Outer Lindblad Resonance, as spiral waves pass through the stars the stars are torqued inward toward the centre of the galaxy by the aggregate gravitational pull of the arm around them. OLRs typically have enhanced neutral hydrogen compared with ionised Hα ratios, a signature of quiescent gas.

If ILRs tend to move stars outward in the disc and OLRs tend to move them inward, where do they balance each other?

The name for this is the *Corotation Resonance.* The CR is that slender hula-hoop rotating around a galaxy which was invoked earlier. In the CR stars and the spiral wave advance forward at close to the same speed (e.g., ±254 km sec^{-1}). In principle CRs are one of the quieter neighbourhoods in a galaxy. The strongest disruptors are relatively lazy giant molecular clouds (GMCs) and occasional supernovae. The CR regime is quite unlike the high-velocity shock fronts from multiple starburst regions that typify galactic life between the CR and the galaxy's bulge.

Although GMCs in the CR rotate around the centre at roughly the same speed as the arm and the stars, they also have their own peculiar velocities. GMCs are migratory — like the 800-lb gorilla they move where they want and sit where they want. The highest velocity component in most GMCs is their z or vertical infall component. Many of them arrive from the galaxy's halo and even from outside the galaxy itself. (See *1*, *2*, *3*, *4*, *5*.) GMCs can easily tidally strip star clusters — and just as easily make new star clusters to replace them. One of the main functions of bars is balancing the angular momentum generated by different parts of the galaxy — especially the tumultuous region in and around the bulge — in a process called virialisation. Bars move gas inward towards their host's bulge. Most of it overshoots and settles in to x_1 orbits that shuttle back and forth from arm to arm across the bar. Whenever there is relatively rapid gas accumulation there is usually rapid star formation and subsequent gas ejection.

This *3-D video slice-through* explains it better than words. Bars play a major role in driving the evolution of disk galaxies and in shaping their present properties. They eject excess matter (mainly molecular hydrogen) from the Inner Lindblad Resonance of the bar into the spheroid of the ancient core and halo, from which it then flows outward to the edges of the galaxy's disc. The outer arms in a spiral galaxy are mainly atomic hydrogen, which does not fuel star formation. Yet quite a bit of star formation does occur out there — witness the Double Cluster and all those beautiful clusters far out in the Perseus Arm. Those clusters are young. Where does the gas come from?

Recall from the hurricane analogy on p.3 that heat flows inward along the spiral waves. In galaxies the heat (gas atoms in motion) gives carbon-based dust grains enough energy to catalyse an atomic hydrogen -to- molecular hydrogen reaction ($2H_1 \rightarrow H_2 + e^-$). Molecular hydrogen is the basic fuel for star formation. Hence galaxies form more stars nearer the centre than in the outskirts.

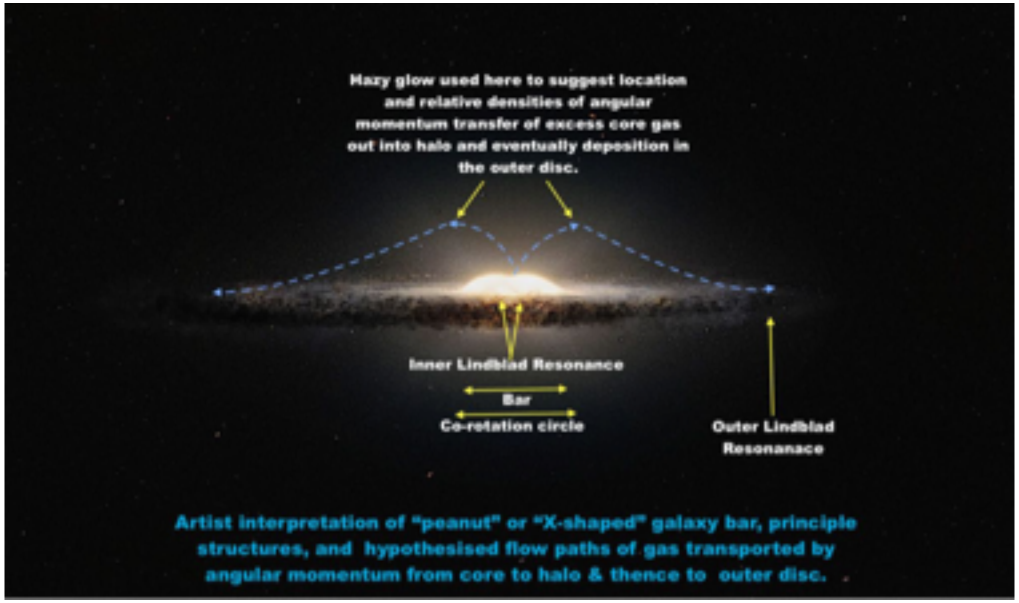


Fig. 11: Bars redirect large amounts of gas into the bulge to fuel star formation. Over time, more gas is delivered to the bulge than it consumes. Angular momentum transfer shifts some of the excess gas into the halo, where it then flows outward. In this sense, galaxies are large-scale heat engines. Note that this drawing is not to scale and that angular momentum transfer does not equate directly to particle mass transport.

Bars are a complex gas machine that combines the conveyor belt with the heat engine. Bars originate as a perturbation in a young galaxy's core, which reshapes the chaotic orbits of spiral-arm gas and stars into slightly elongated structures which evolve their own set of processes and contents. There are differences between the effect a bar has on a spiral arm's gas and a spiral arm's stars. The two respond differently to the excess gravitational potential of a galaxy core (and later, its bar).

Even though a spiral arm's gas forms only about 10% of its mass, its mutable behaviour effects enormous changes in the parent galaxy. Interstellar gas is shifted from a galaxy's spiral arms toward the core by the bar's gravitational churn. Violent bursts of star formation follow, with subsequent supernovae. Supernovae expel large quantities of gas into the galaxy's halo, where some of it eventually ends up replenishing the galaxy's disc far out in its outskirts.

The perturbation originates in a rotational instability in the Inner Lindblad Resonance (*Fig. 9 above*). ILRs destabilise the already modest infall of gas along the spiral arms into the core. At first the bars are short, broad-shouldered, and vertically thin. Bars in galaxies with larger central mass concentrations are shorter, but wider.

Over spans measured in hundreds of millions of years bars progressively lengthen and become slimmer along their lengths, but also thicken vertically. Over time bars feed enormous quantities of gas from the spiral arms into the galaxy's bulge. Only a certain portion of it is actually retained by the bulge. The rest is disposed of in three ways:

1. Massive gas inflow into the bulge initiates a long-lasting round of star formation. The Milky Way's most massive star clusters—Arches, Quintuplet, Central—are very young, massive, and hot in a part of a spiral galaxy that gave birth to and still hosts the oldest stars in its history. Bar inflow also feeds supermassive black holes; the Milky Way's BH is 4.5 million $M_\odot$.
2. The galaxy's core can consume only so much inflowing gas by making stars. Part of the excess goes into fuelling a new central structure: a *pseudobulge*. (NGC 1365 Fornax has a prominent pseudobulge.) Gas flowing inward along bars produces dense, thick inner bars, and eventually mini-spirals within the pseudobulge. The bulge thickens axially (vertically) until the inner bar buckles upward from instabilities produced by stars gravitationally "scattering" off the bars. Scattering is a heating process. It injects the additional kinetic energy of random motion into the system. The system responds by moving the energetic particles further apart. Rotation turns a local wave shape into the vertical buckle of a pseudobulge. See *1*, *2*, *3*, *4* and this convenient *overview compilation*.
3. Bars transfer angular momentum from the core to the galaxy's outskirts. Angular momentum in this context is not composed of particles, but rather the combined energy of myriads of particles whose momentum has been stored up in the galaxy in the form of rotational velocity. The angular momentum emitted from the Inner Lindblad Resonance of the bulge is absorbed at first by resonant material in the spheroid (i.e., the ancient core and halo). From there the angular momentum is transferred to the outer disk.

Bars eventually degrade themselves by their very efficiency — an event called "bar suicide". Over-accumulation of mass in the galaxy's centre eventually disrupts the orbits of the bar's stars, which in turn decays the bar. As the bar dissipates from the pseudobulge outward it is replaced by a newly emerging spiral system propagating outward from the bulge (*see Fig. 30 of NGC 1672 Doradus below*). Bars are transient phenomena in the lives of spiral galaxies. They decay over time, transforming galaxies from barred spirals back into more traditional spiral patterns. This begins the cycle anew — a strong bar weakens into a new spiral, which in time grows massive enough to feed a new bar.

What do stars do in those bars?

Galactic bars are not as serene as their languid appearance would suggest. They extend and contract in length and thickness in relation to the density of the spiral arms which feed them gas and the bulge which consumes that gas. Gas clouds in spiral arms are torqued sharply into taffy-like streams which distend into rotational families that look rather like an auto-buff's idea of a really bad-news race track. Galaxy bars are lungs which in effect breathe continuous fresh air into galaxy's bulge — and then exhale the unconsumed air to fuel the bar on the other side.

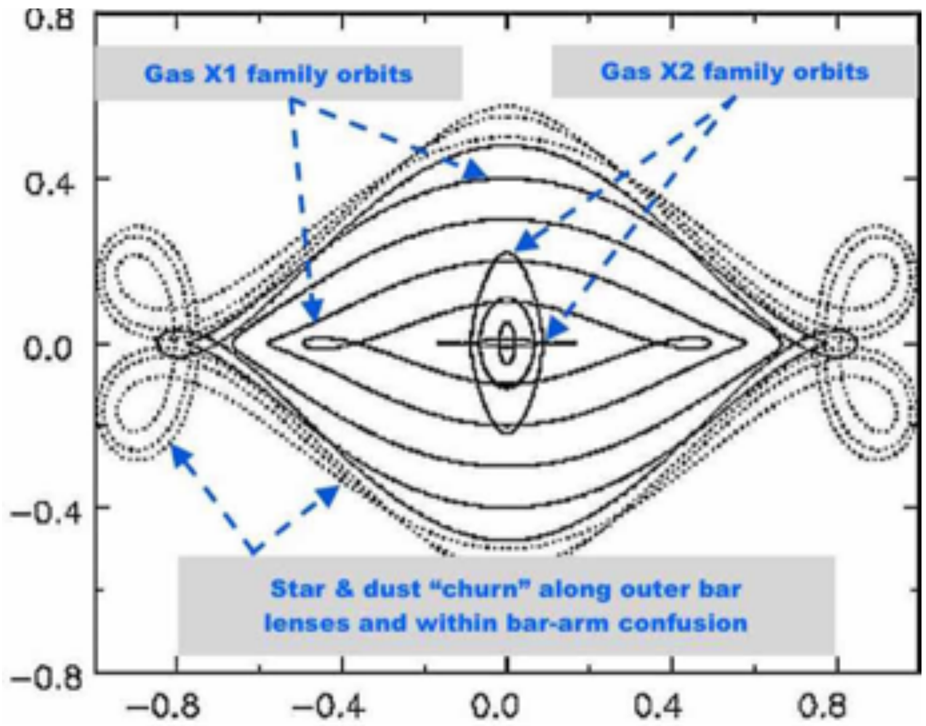


Fig. 12: The torque and shear forces that disrupt the spiral arm's gas clouds are so strong that they decouple gas from its clouds and stream the gas into a featureless surface. Two orbital families result: those which shuttle back and forth from spiral arm to spiral arm, named x_1, and a perpendicular family, x_2, that eventually will evolve into a pseudobulge. *Source:* *Bournaud & Combes 2002*.

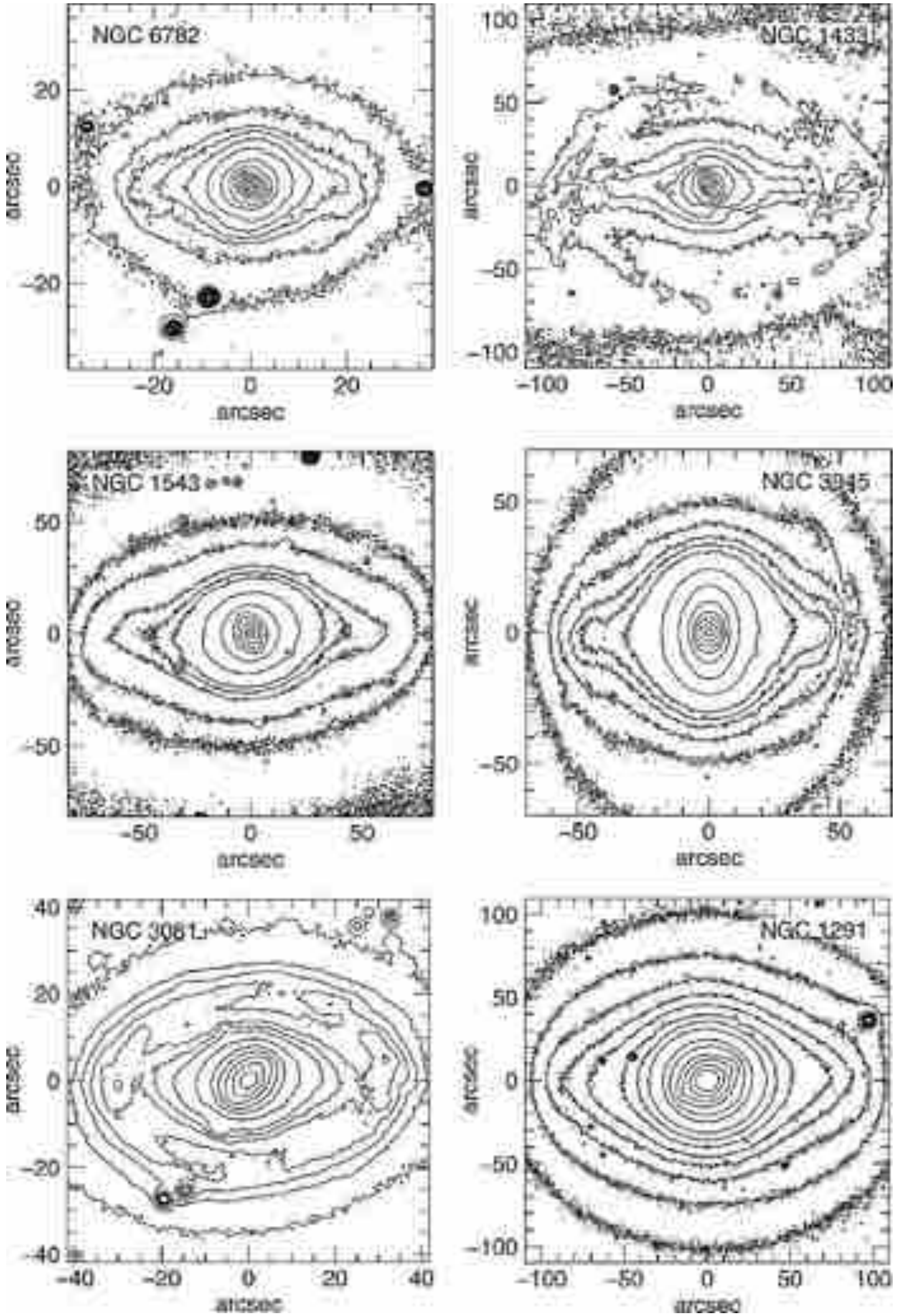


Fig. 13: When galaxy bulges accumulate *bulge-to-bar mass ratios* of ~62%, shear forces induced by the bar's orbiting families (above) induce the formation of a secondary bar inside the ILR of the bulge. The new inner bar has the same features as a spiral arm bar, e.g., a surface brightness profile that rises dramatically to a peak in the centre. The formation of a nuclear bar is strong evidence that a galactic centre is dominated by a pseudobulge. Pseudobulges become unstable at high densities. They feed the galaxy's central black hole so violently that the result is an Active Galactic Nucleus or AGN. The AGN galaxy M77 in Cetus is a frequent stop on the amateur community's observing list. *Source*: *Kormendy 2004, Fig 14.*

The only thing than can make a river turn a corner is a riverbed. But there is no riverbed in a spiral galaxy. Why would a circularly spinning galaxy spontaneously form a horizontal bar that ends up disrupting the entire middle part of the galaxy?

Inside a spiral, the surrounding medium behaves like a gas mixed with many solid particles, i.e., a fluid. Seen on a larger scale from the outside, galaxies look like a viscous fluid being churned by a paddle. Let us call this paddle "Inner Lindblad Resonance". The paddle originates because the velocity of a galaxy's rotating fluid is higher than the *Reyleigh discriminant*. Even a tiny disturbance can cause an eddy in the rotating flow. Galaxies are constantly perturbed from outside by the tidal stresses of nearby galaxies. Once an eddy forms it quickly strengthens into a pimple-like bump. A counterpimple forms on the opposite side of the eddy because of the natural epicyclic oscillations of waves in fluids.

When the pimple extends far enough into the viscosity that tiny eddies form behind it, we have a paddle, or rather, a bar. If the bar's rotational (orbital) speed around the centre is faster than fluid's natural oscillation frequency, a self-reinforcing resonance is set up — the Inner Lindblad Resonance. Inside the circle the fluid wants to rotate around the centre; outside the ILR the fluid wants to flow along the paddle. A short paddle (newly developing bar) creates tiny eddies along its lee side. Those eddies propagate all along the length of the bar until in time they reach the opposite end. There the eddies mix with the freshly arriving fluid on the front side of the bar as the bar churns around and around. The result is chaotic turbulence. The region this turbulence occupies is called a Lagrange point. Rotating groups such as star clusters and galaxies have five *Lagrange points*.

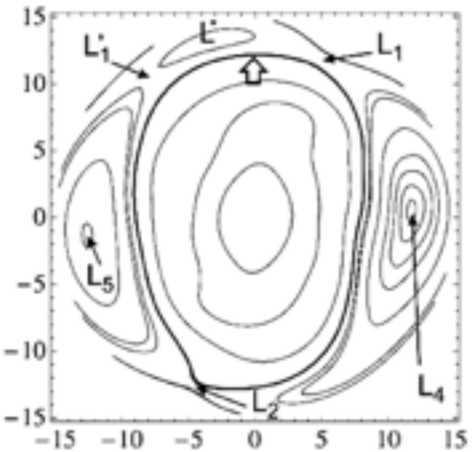


Fig. 14: Lagrange points L_1 and L_2 in NGC 1300 are like eddies of a paddle that stirs its rotation. *Source: Athanassoula 2012*.

Rotational vectors flow around a central force unless disturbed by an outside force.

Perturbation vectors respond to a one-time disruption, then carry on until disturbed again.

Shear tensors are a common flow made of many individual perturbation vectors responding continuously to external forces.

Fig. 15: At an inner resonance, a star's orbital speed is increased, moving the star outwards, and decreased for an outer resonance causing inward movement.

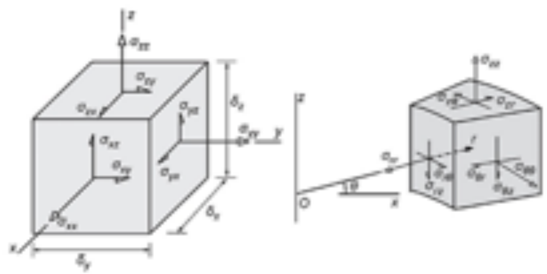


Fig. 16: On the scale of a galaxy, arms and bars behave like a fluid, not a gas. The myriad particles or stars and gas clouds each has its vector within the galaxy's gravitational well. The combined flow of these countless individual vectors is described by a branch of mathematics called tensors. As the above diagram shows, they can be bogglingly complex. For our needs here, the shear stress tensor of a bar-arm interaction is a river made of many droplets united by a riverbed into a coherent flow.

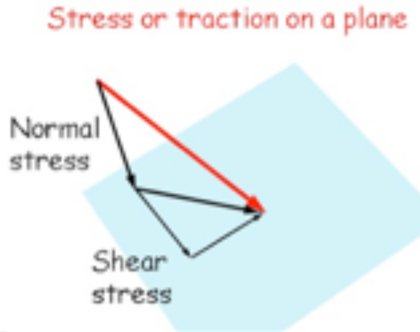


Fig 17: A shear tensor is a way of calculating the actual direction of multiple interacting forces. Calculating the cumulative effect of trillions of particles moving in spacetime requires enormous computing power.

Sheer stress

The bar-arm confluence which so beguiles our splendid Milky Way arching overhead is a walk-on part in an allegory as complex as a literary epic. For a quick refresher, *start here*.

The word *shear* has likewise played a seeming bit part in all this discussion. Yet it is in fact the main player — not merely in our modest local drama above but in the way the universe itself shifts its energies about. We need to look at the word *shear* not as local event but as univeral function.

Shear is a verb: "break off or cause to break off, owing to a structural strain". That denotes an event that's already concluded. To give the term scientific utility we need to first phrase it as a definition, not an event: "a strain produced by pressure in the structure of a substance, when its layers are laterally shifted in relation to each other", which is to say: it can happen any time, anywhere. The reason we put it into a noun is so we can assign a numerical value to it: *shear stress*. Finally, we need to turn that value into a mathematical function we can apply uniformly to any appropriate situation. In astrophysics it is called a *shear stress tensor* (1, 2, 3, 4).

South Africa's NASSP (National Astrophysics and Space Science Programme) website "*Astrophysical Fluid Dynamics*" illustrates some examples:

Fluid dynamical processes are the driving force behind most fundamental processes in the universe, i.e. spiral density waves in galaxies, triggering bursts of star formation in the spiral arms as it passes through a region, solar and stellar flares, stellar evolution, instabilities in stars giving rise to stellar pulsation, accretion processes in binary systems, as well as the super-relativistic jets ejected by black holes in the heart of galaxies, and many others.

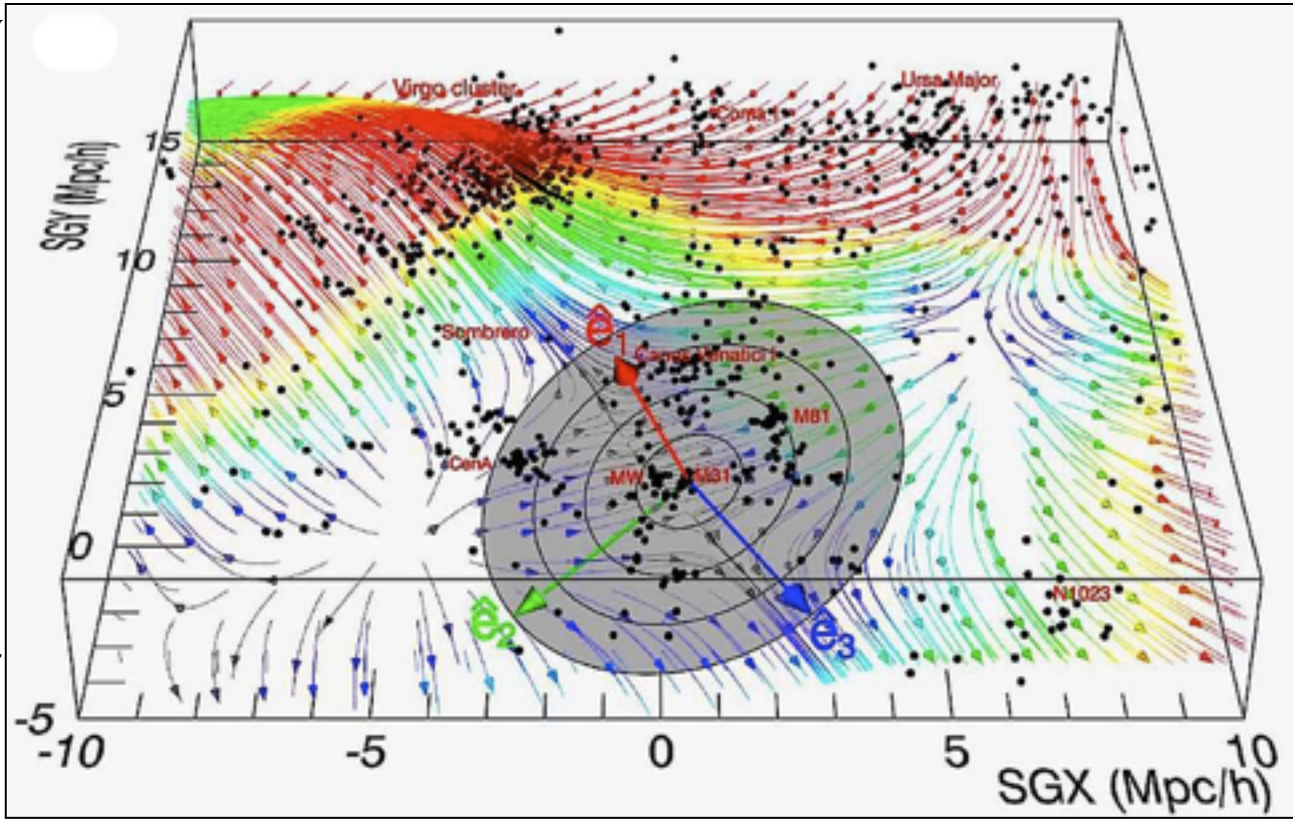


Fig. 18: The bar-arm confluence spanning the sky from Aquila to Norma is a modest example of universal physical processes that give shape to the entire Cosmic Web. In this image by Daniel Pomarède, the Local Group, M81 Group, Centaurus Cluster, and Sculptor Group are all infalling toward a shear stress tensor $\hat{\mathbf{e}}_3$ connecting the Virgo Supercluster with the Perseus-Pisces Supercluster (located off the bottom of the diagram at about the five o'clock position). As the galaxies converge toward their individual common centres (e.g., the Local Group), they are simultaneously being pulled toward the Virgo Supercluster. Each galaxy has its own *vector*; each galaxy group has its own combined *vector field*; and the combined vector fields of all of them together are shaped by the Virgo Supercluster *shear stress tensor*. A tensor can be thought of as a supra-vector field made of many other vectors. Tensor fields are rather difficult mathematically, but visually they are rather simple — to say nothing of beautiful. The profound role stress tensors play in the cosmology of the universe has become apparent only in the past few years. *Image source*: Libeskind 2015.

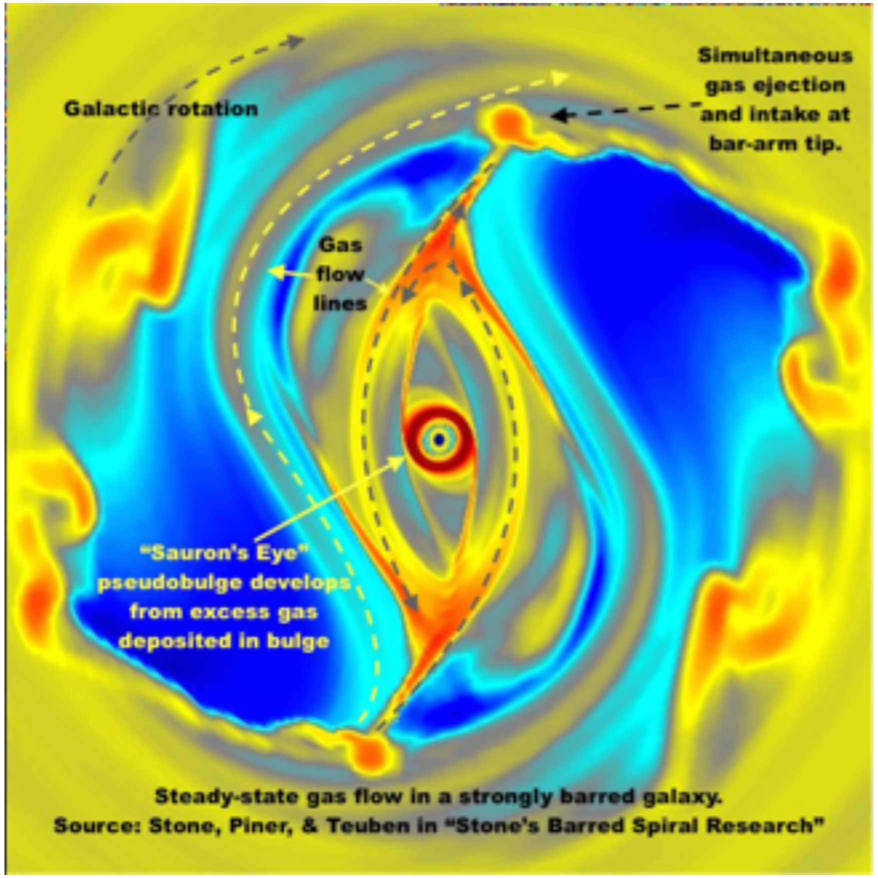


Fig. 19: Still frame from six-second 1.3 MB movie simulation of gas flow in a late-stage barred spiral galaxy by Princeton's Jim Stone. Titled *Gas flow in Barred Galaxies* (*view & download the sim here*.), the sim portrays gas behaviour only; no stars are involved. The sim reproduces the more obvious features found in real galaxy bars — recirculating gas flow within the bar, gas recycling into spiral arms at the co-rotation resonance, how gas flows into incoming shock waves from the opposite dust lane and then back out to collide with incoming spiral arm flow. The sim vividly portrays how gas expulsion from bar tips into spiral arms sets the stage for massive star formation at the confluence of spiral arms and galactic bars — exactly what we would see in Aquila and Norma if we could see through the intervening dust.

How to make something terribly complex terribly simple

Galactic evolution is caused by the heating effect of random motions. "Heat" means the aggregate velocity of the system's myriad particles. "Hot" means a lot of motion in a given volume. If the centre of the volume gets hotter than the periphery, the rising particle velocities (heat) attempt to to get back into balance by flowing toward the less hot regions. When those regions receive the heat, they expand and therefore cool. The overall effect is to cause the system to spread out. Systems that behave this way are dominated by velocity dispersion. Dispersion is the change in random motion as one goes from one side to the other. A dispersion curve looks like a bell-shaped curve, with the highest velocities at the very top of the curve and the outskirts near zero.

The specific heat of a self-gravitating system is negative, which is to say that excess heat makes it expand outwards in order to come back into balance with its surroundings.

Why is this so? Consider an equilibrium system of N particles of mass m, radius r and three-dimensional velocity dispersion v.

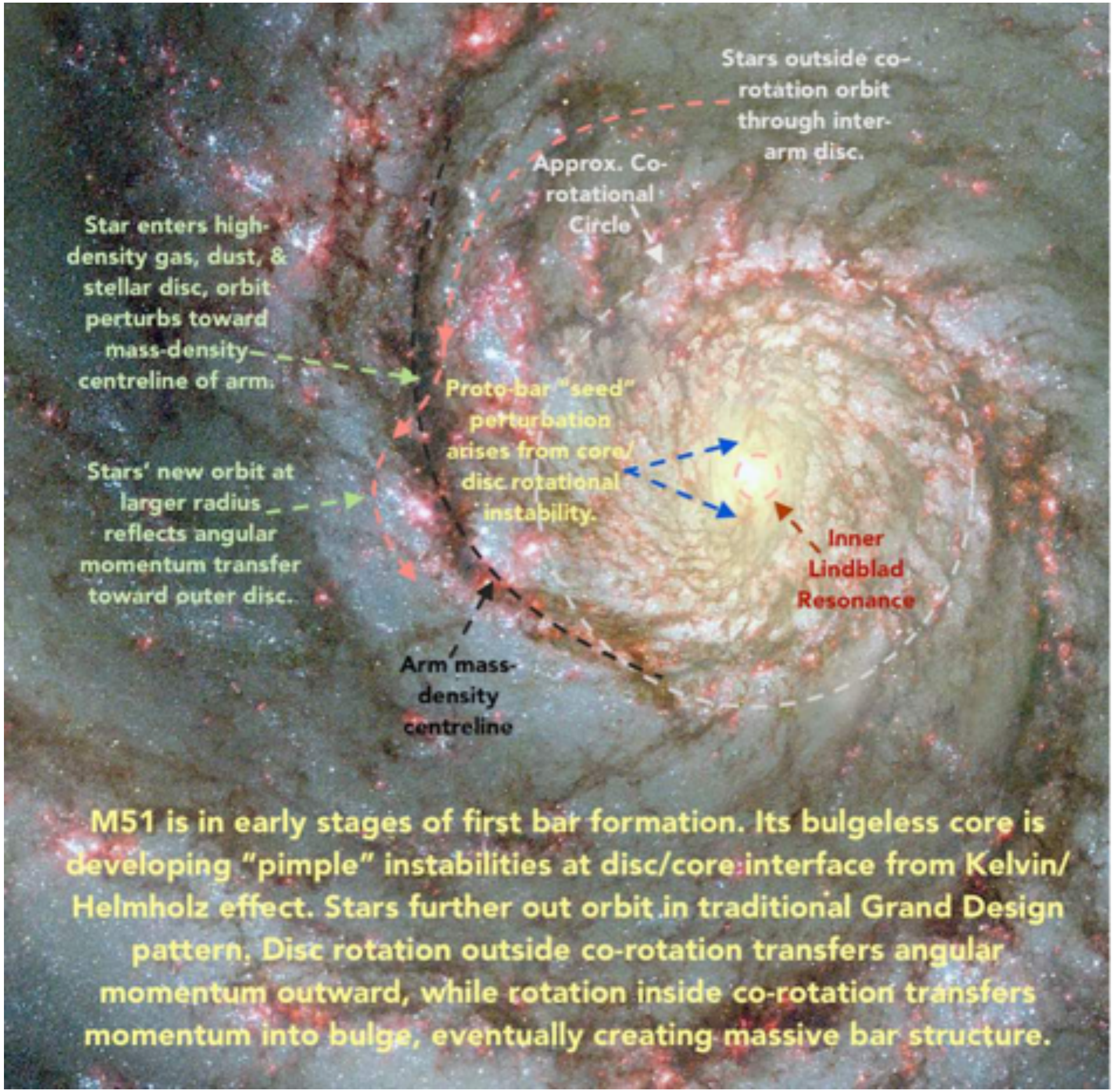
The virial theorem tells us that 2KE + PE = 0, where KE means kinetic energy and PE is potential energy. The number 2 is in this picture because it takes as much energy to bring a system back to equilibrium as it did to make a mess of it in the first place. Put another way, it takes as much energy to lift a book from the floor to a table as it does to return the book to the floor. We don't notice the latter energy because gravity is doing the work for us.

- So, $\mathrm{KE} = Nmv^2/2$ and the potential energy is $\mathrm{PE} = -G(Nm)^2/r$.
- The total energy $E \equiv \mathrm{KE} + \mathrm{PE} = -\mathrm{KE}$. The negative minus sign tells us that it is a bound system (positive kinetic energy makes a system fly apart).
- The temperature of the system is measured by v^2, that is, $mv^2/2 = 3kT/2$.
- Hence the specific heat $C \equiv dE/dT \propto d(-Nmv^2/2)/d(v^2)$ is also negative. G is the gravitational constant and k is Boltzmann's constant.

These are properties of a system that is supported by the dynamic heat produced by its continuously interacting particles. The rate at which the system evolves depends on how efficient is its heat-transport mechanism.

=Adapted from Kormendy 2013.

Where does angular momentum transfer happen?



Certainty is a fleeting joy in astronomy. Numerical values are only as reliable as the measurements underlying them. Galaxies are notoriously prone to misleading evidence. *Differential extinction* is a bugbear to optical-band astronomy. *Magnetohydrodynamic quenching* of turbulence is subject to local density fluctuations. *Small number statistics* and *selection bias* negatively impact the input reliability of N-body and constrained realisation simulations. An example of how a new and more carefully constrained observation set can upset established apple carts is *Reid et al., 2009*, who used VLBI measurements of masers in 18 high-mass star-forming regions to refine the model of our own Milky Way home galaxy. Their findings were:

(1) Star-forming regions are orbiting the Galaxy about 15 km/s^{-1} slower than expected for circular orbits.
(2) The rotation curve was thought to be nearly flat with increasing Galactocentric radius, but this value was superseded four years later by *Sofue 2009* (Fig. 9 above).
(3) The angular velocity of the Sun (30.3 km s^{-1} kpc) is significantly larger than the IAU value of 25.9 km s^{-1} kpc.
(4) Galactic centre–Sun distance R_0 = 8.4 ± 0.6 kpc.
(5) Circular rotation velocity of the Sun around the galaxy is V_0 = 254 ± 16 km s^{-1}. (The old value was 220 km s^{-1}.)
(6) The angular velocity of the Sun V_0/R_0 = 30.3 ± 0.9 km s^{-1} kpc^{-1}.
(7) The Galactic bar rotates as a solid body with a pattern speed of 220 km s^{-1}. This is 31 km s^{-1} slower than the spiral arms he bar intersects.
(8) the parameters are very similar as Local Group galaxy M31 Andromeda, suggesting that their dark matter halos are similarly massive.

Further information on M51 here: 1, 2, 3, 4.

Fig. 20: As a star passes through the arm, the gravitational potential of the spiral wave veers the star outward from its circular path. When the star eventually advances through and out the front side of the arm, its orbit returns to circular, but is further out from the centre. ILRs usually develop near the outer edge of the bulge where it joins the arms or a bar.
Image source: NASA/ESA Hubble Legacy Archive.

What does angular momentum transfer accomplish?

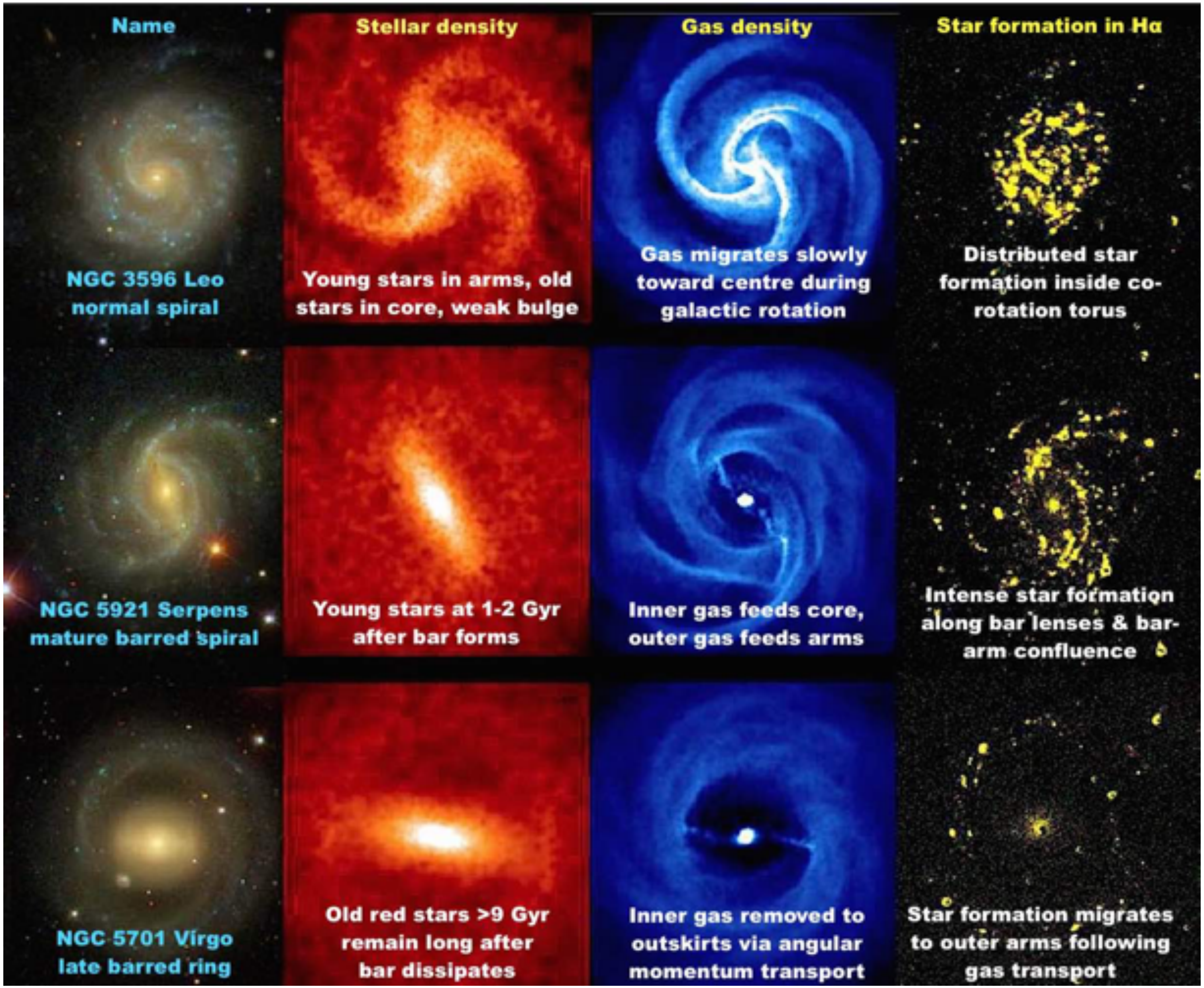


Fig. 21: NGC 3596, NGC 5921, and NGC 5701 show us three stages in barred galaxy evolution.

The angular momentum (energy from rotation) of a galaxy's stars, gas, and dust originates in the rotating frame of its spiral arms. The path traced by each star or gas cloud's momentum is influenced by the gravitation of the entire galaxy. In normal spiral arms stars and gas follow a roughly circular track rotating around the galaxy centre. If galaxies had no gas and the stars were all identical, the stars would rotate around in nice, tidy circles.

But galaxies *do* have gas. Though gas makes up only about 10% of our Milky Way's disc mass, it is clumped together in giant clouds which exercise an outsize influence on the rotation paths of nearby stars and star clusters. Without bars, the spiral arms would slowly feed into the bulge, eventually depleting the galaxy arm gas.

The length and strength of a bar is influenced by the amount of angular momentum the halo can absorb, the length of the bar's radial extent, and the velocity anisotropy (shear forces) of its components. There is a strong correlation between bar strength and the amount of angular momentum it injects into the halo. Part of the angular momentum is absorbed by the halo, especially near the disc plane. Halo rotation correlates with the bar strength, but is very modest indeed: the halo's circumference just above the thick disc advances only 5° – 30° over a period of 10 Gyr due to angular momentum transfer from the core.

All the rest of the angular momentum ends up in the outer disc, where it feeds future star formation. Bars are like a heartbeat pumping fresh blood throughout the system to keep it healthy. These three galaxies reveal the different stages of the overall process.

Image source: Gavazzi et al 2015.

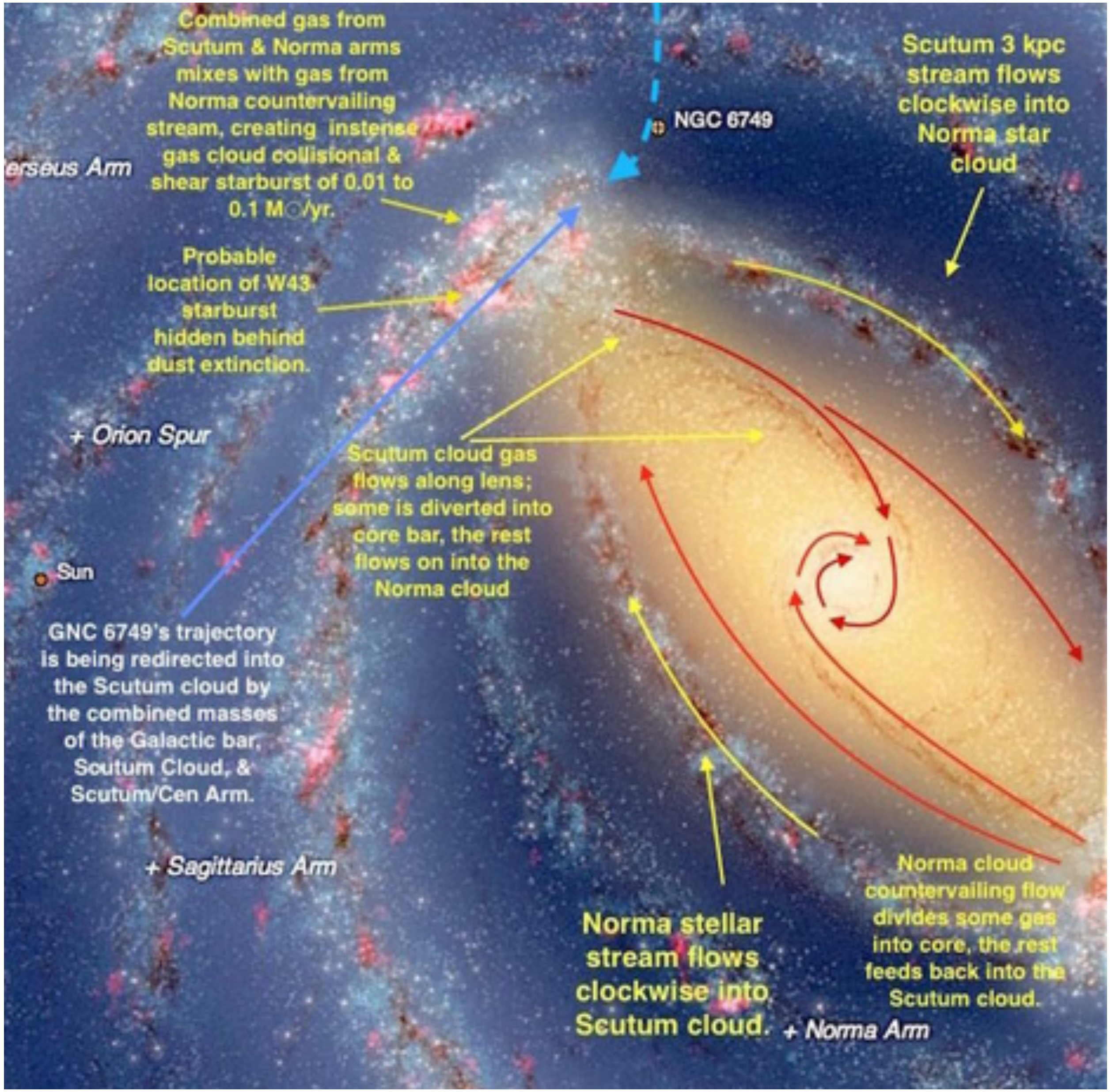


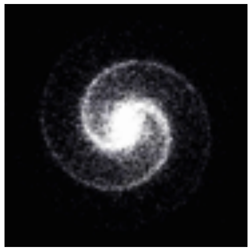
Fig. 22: The beclotted character of stellar and gas populations in spiral arms changes dramatically when they enter the chaotic bar-arm confluence at the outer tip of the bar. Star formation there is intense — e.g., the W43 cloud complex in Aquila. In many galaxies the spiral arm stars are de-orbited into lens-like star steams like the 3 kpc stream that flows from Scutum to Norma on the forward side of the bulge and in the opposite direction on the rear side of the bulge. The spiral arm gas that survives churning, torque shears, and magnetic fields in the confluence is revectored into long elliptical orbits along the main bar. The gas velocities are so high and pressure gradients so low that gas cannot clump into dense clouds the way it does in discs. Most of the gas that falls into the bar eventually becomes stars in the chaotic bar tips.

The most interesting fate is what happens to the dust filaments in spiral arms. Dust that forms in galaxy arms comprises about 0.1% by particle count of a given volume of gas. The gas-dust mix rotates in roughly circular manifolds around the galaxy core. The term "manifold" means a self-coherent tube-like feature that encircles the galaxy rather like a hula-hoop made out of spaghetti. In this analogy, the tomato sauce is the galaxy's gas and the stars are the bits of mushroom. Manifolds do not have solid walls; matter can enter and leave them, but tends to stay inside because of internal gravitational and magnetic fields. Manifolds were originally artificial constructs devised to make *N*-body sims behave like real galaxies. In 1992 Lia Athanassoula pointed out that the dust filaments visible on the inner sides of spiral arms were once dispersed but now stream together as its gas cloud deforms into comet-shaped clumps upon entering a spiral arm. Being dense but of tiny mass, the dust overshoots the bar. It is slowed just enough to be gravitationally streamlined along the front side of the bar. Measurements of the gas velocities on both sides of the bar filaments revealed that large velocity gradients existed in dust filaments after they crossed galaxy bars.

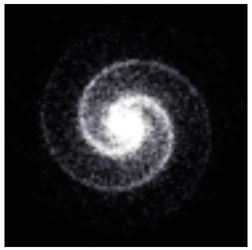
DIY galaxy sims

There is a formidable and growing, array of cosmology and galaxy-scale sims produced by the likes of *iLLustris*, *CLUES*, *Magneticum*, *Bolshoi*, *Eagle*, *ICRAR*, *SILCC*, and a host of other institutions and individual astronomy professors. Sims represent the universe in 4-D, whereas observational astronomy produces mainly 2D snapshots while numerical astronomy produces 3-D graphical renderings that are hard to visualise in real-sky terms. The sophistication of sims and visualisations demonstrate how various phenomenon in the universe actually behave as we observe them.

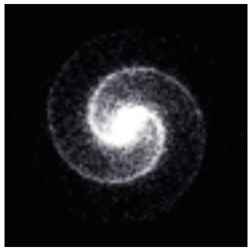
Sims have moved out of the mainframe world and onto your desktop. Any computer-literate amateur with a reasonable knowledge of coding and a basic grasp of astronomical physics can make their own simulations for self-study or to show friends. There are numerous pre-made algorithms and source code libraries which can be downloaded to a home computer. A good place to start is the *BeltOfOrion.de* website, which is devoted to home-brew enthusiasts who want to make their own. The BeltOfOrion *Galaxy Rotation* workshop provides plenty of inspiration to keep us playing in the starry sandpile for years to come. Here are four examples:



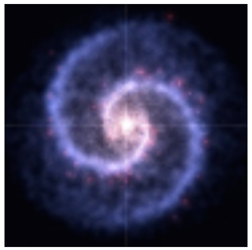
Rotation producing winding problem.



Orbits predicted by Lindblad rotation.



Orbits predicted by density-wave theory.



Combined stars, nebulae, & H2.

From basic websites like this you can advance to the *Astrophysical Source Code Library* produced by *ASCL.net*. A YouTube search using phrases identifying specific phenomenon, e.g. *star cluster* or *galaxy formation sims*, will bring up many others. And if you're keen to know how they did this in the Bad Old Days (1960s), take a deep breath and *start here*.

Fig. 23: In a classical spiral the disc consists of gas and young stars while the bulge is made of the galaxy's oldest stars. The core of M94 does not have an old red component left over from the galaxy's original formation but rather a bright intense star-forming Grand Design spiral in miniature. The unusually bright outer disc shimmering with young massive stars suggests that considerable molecular hydrogen fuel was transferred there from the highly active core region during previous bar formation-dissolution episodes.

Case study: NGC 1300 Eridanus

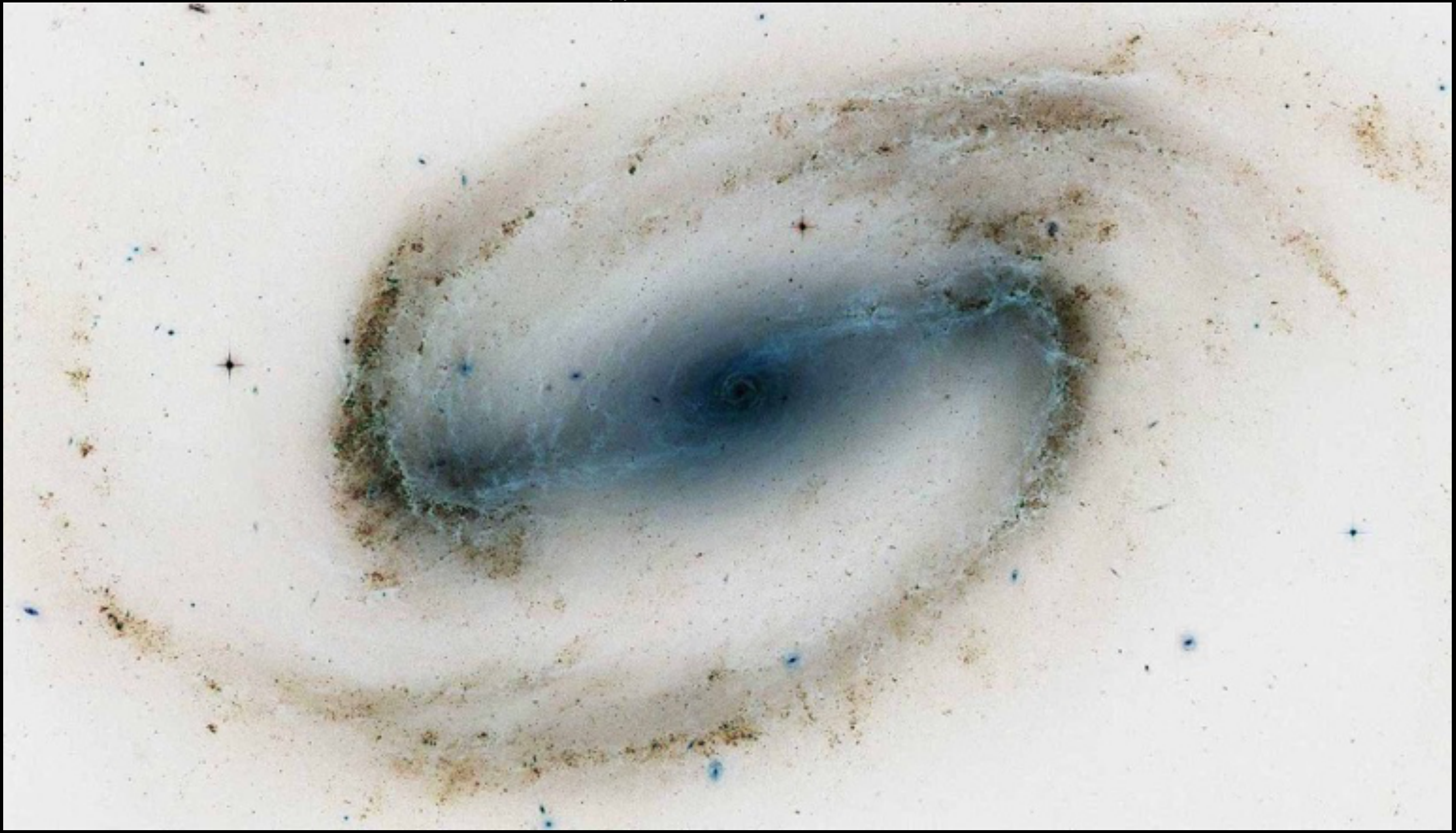


Fig. 24: NGC 1300 Eridanus is at a more advanced stage of bar development than the Milky Way's bar in its present stage. The colour scale of the image has been inverted to highlight the filamentary character of dust streams in the bar compared with the diffuse gas in bluish tones. Note how the dust filaments shift from the inner side of the spiral arms near the bar to the outside of the bar on the far side of the bar axis. This indicates that NGC 1300's co-rotation circle lies inside the spiral arm where the bar and arm join (i.e., the bar tip). About 60% of NGC 1300's mass lies inside the co-rotation circle. Each of NGC 1300's bar-arm confluences has baryon masses great enough that their gravitational potential rivals that of the bulge. Three huge mass centres occupying the length of the galaxy bar sets up competitive gravitational wells that disturb the orbits of individual stars in the arms. The strikingly quiet voids between the arms and the bar suggests that the normally circular orbits of stars in a spiral galaxy's arms have been deformed into non-circular shapes.

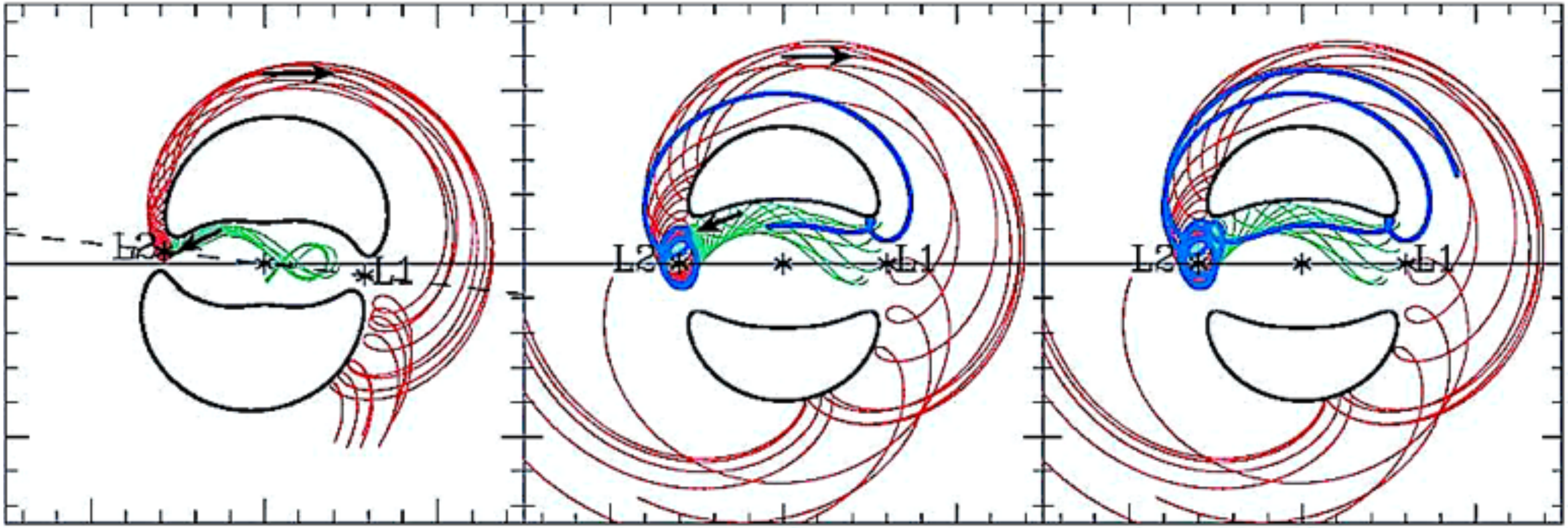


Fig. 25: Most accounts of galactic bars lavish attention on the bars. They are indeed beautiful, complex, and intricate, in the rather stiffly formal way that Bolshoi ballets were precisely structured. However, glance away from the pretty *pas de deux* in centre stage and take in the large view of the intricate fluttery footwork by the *corps de ballet* on the sides and rear stage. Imagine those toes as stars. NGC 1300's long, graceful spirals look like they are curling inward to an inevitable fate of merger with the star factory of the bulge. Alas, not so, and for two quite different reasons. First, those arms are composed of gas as well as stars — the gas is about 10% of the arms' total mass. The gas (curlicue blue lines above) tends to be gravitationally bound to its nearby surroundings and is swept along the arms toward the bar-arm confluence. Second, the stars are point masses that have to contend with three high-mass gravity wells: the bulge (the ✻ in the middle above) and the L1 and L2 Lagrangian points centred on the left and right bar-arm confluences. To stars at different locations in the arms and interarms, each of the three wells competes for the stars' orbital attention. As the stars move around the disc (CCW in this case) their relation to the three gravitational wells constantly changes. Stars near the L1 or L2 Lagrange points (red lines) eventually adopt kidney-bean or banana shaped orbits so long as they remain inside the heavy blue regions above. If they wander outside the blue "bananas", angular momentum transfer outward from the core alters their orbits such that they they end up spreading OUTWARD. Recall the spiral arms of terrestrial hurricanes spreading outward from the storm. In a 2012 paper, *Manifold-driven spirals in N-body barred galaxy simulations*, Lea Athanassoula summarised, "The radial extent of the arms increases with time, thus bringing about a considerable increase of the disc size, by as much as 50 per cent in about 1 Gyr." *Source*: Athanassoula 2005. Image from Athanassoula 2012.

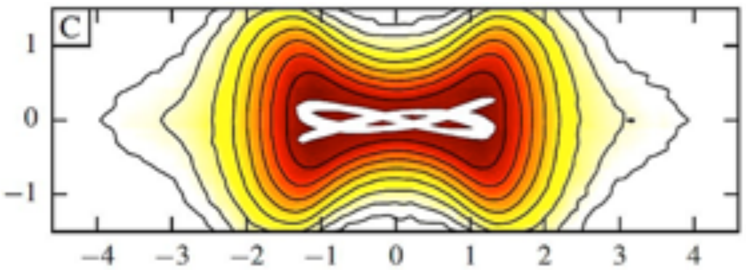
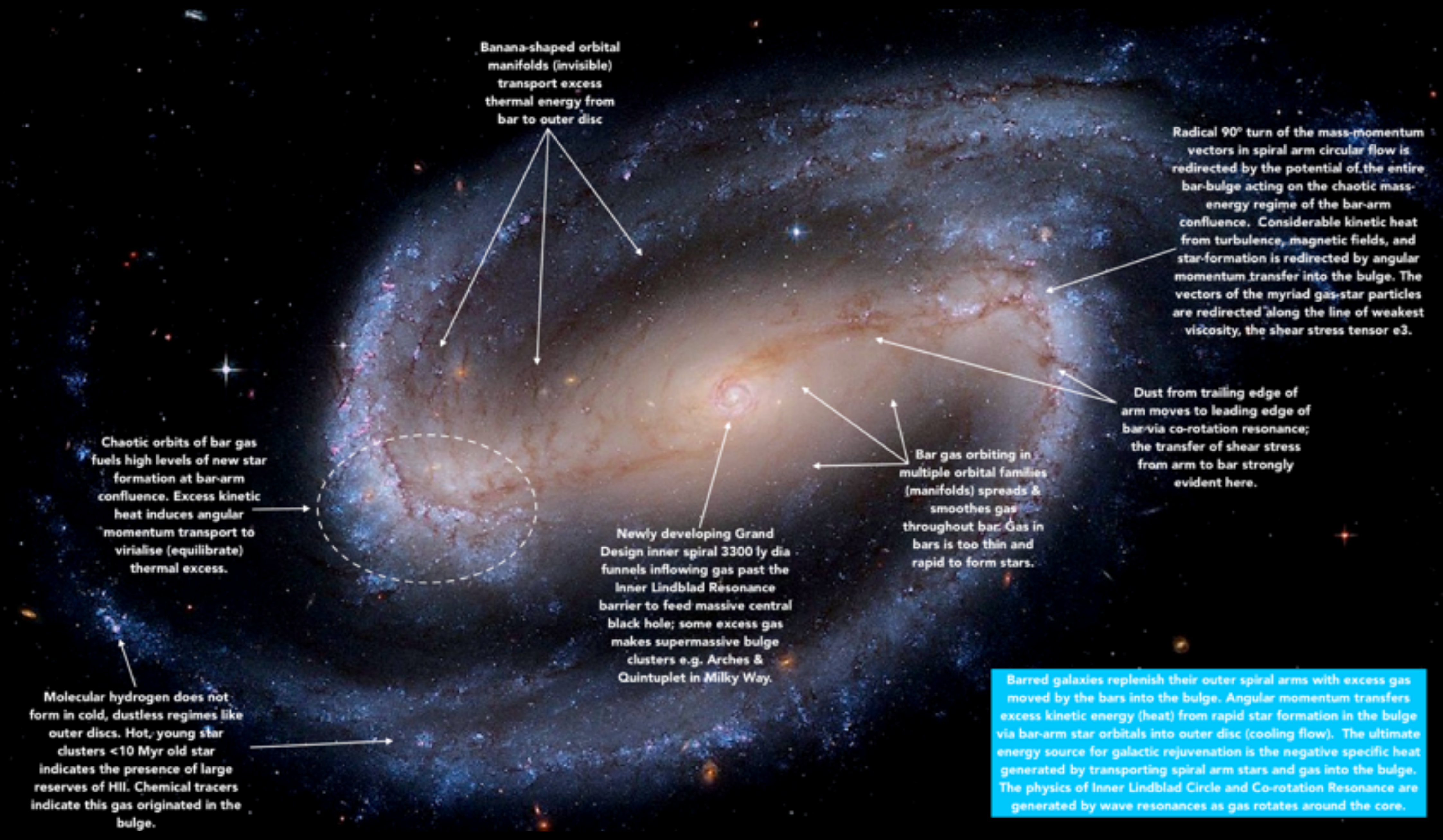


Fig. 26: Banana-shaped stellar orbitals are not related to the x_1 family orbitals shown above that traverse a galactic bar. Instead, they move rather aimlessly in the interarm region until either captured at one of the Lagrangian points, or escape into the outer disc as part of the galaxy's angular momentum transfer from the bulge to the Outer Lindblad Resonance. This drawing does not depict orbital paths, but rather the energy isopleths that collectively regulate bar shape and strength. *Source*: Portail et al 2015.

NGC 1300 decoded



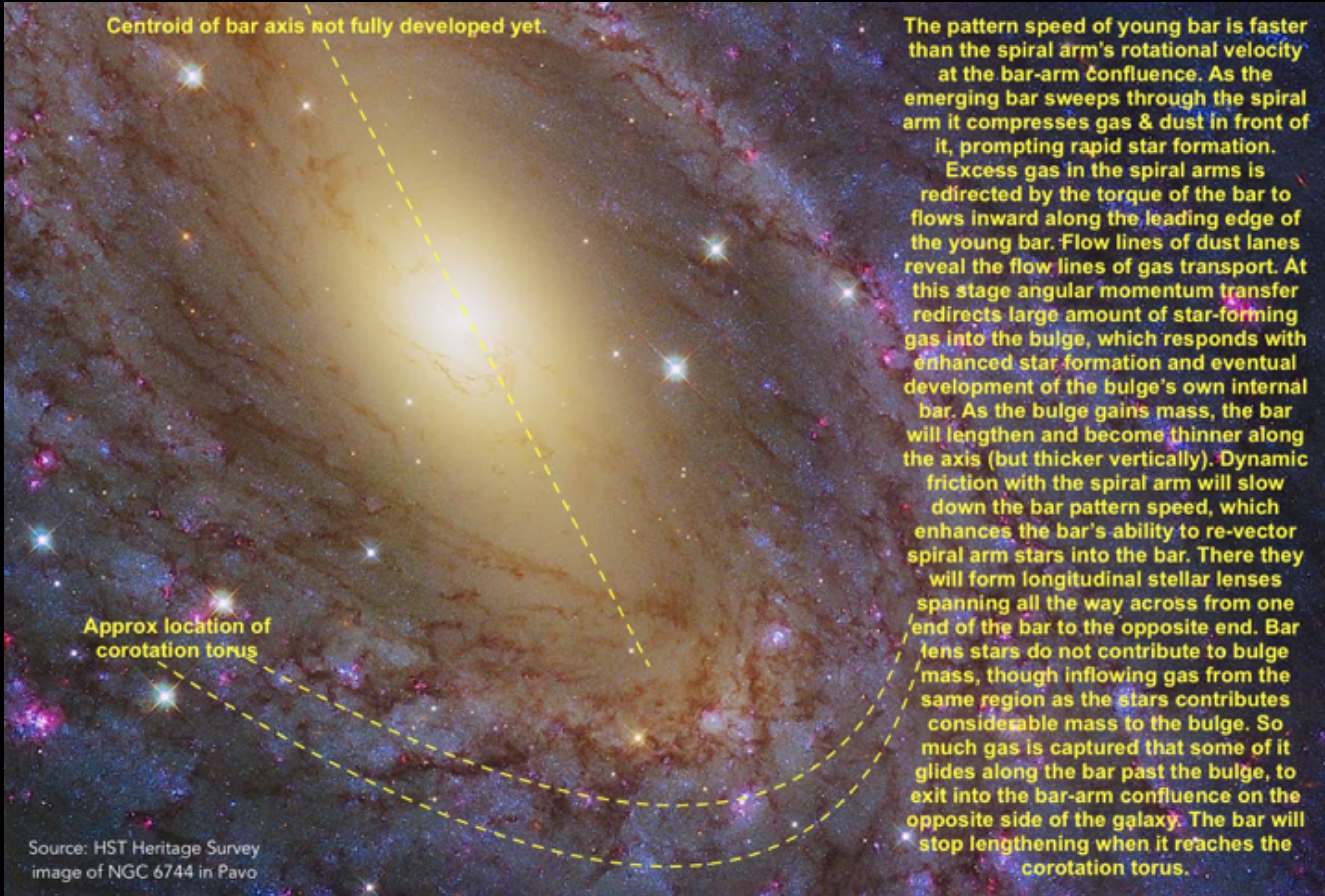
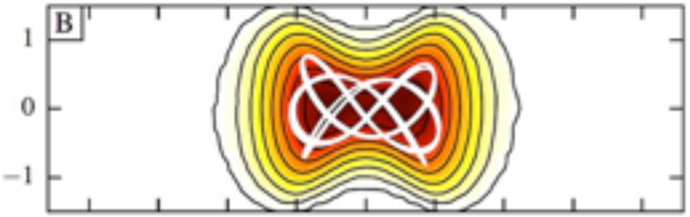


Fig. 28: NGC 6744 is in the early stages of developing a bar. Until about 300 to 500 million years ago it was a normal spiral galaxy. Spiral arms do not deliver much gas into the core of a galaxy and the bar-arm connection is both weak and fragile. A rotational Kelvin-Helmholz instability caused "pimples" of massed gas to form at the place where the arms joined the core. This initiated a phase in which more and more gas was diverted to the core, increasing its mass and therefore rotation rate. Removing gas from the spiral arm to funnel it into the core became a self-reinforcing gas-flow/mass-transport mechanism out of which a true proto-bar forms such as NGC 6744's here. It is presently immature but will thicken and elongate until it becomes discernible as a true bar.



X-ray and near infrared images of NGC 1672 reveal this core orbital-support pattern of a classic pseudobulge.

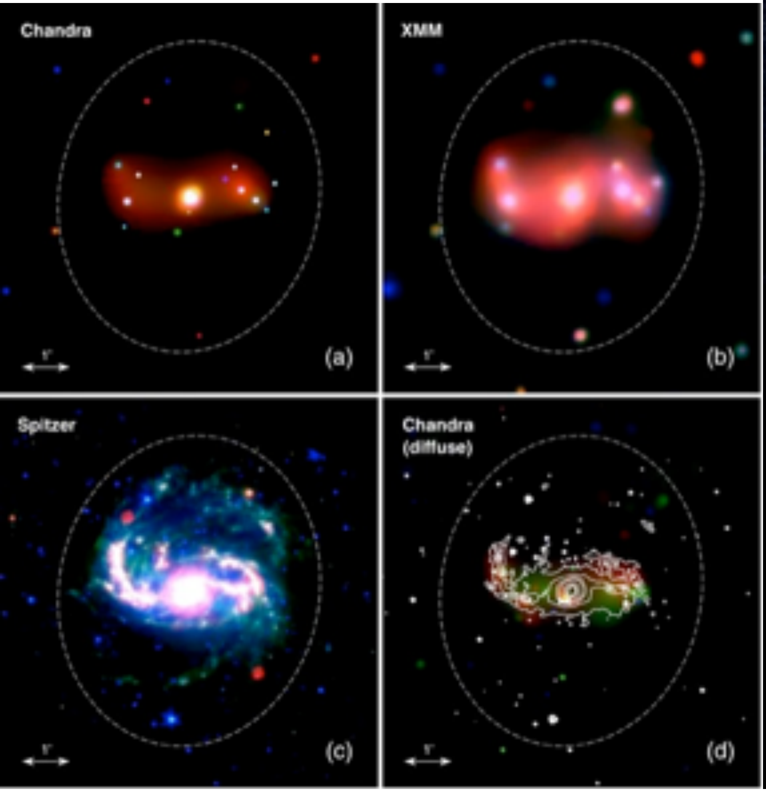


Fig. 29: As a prototype of a barred spiral galaxy, NGC 1672 in Doradus differs from normal barred galaxies in that it has two sets of spiral arms with a truncated bar joining the inner spiral to the outer disc. NGC 1672 evidences intense star formation in both the inner core bar and in the four outer spiral arms that feed gas into the inner two-arm spiral. Two of the outer arms appear to fed gas directly into the inner bulge-bar, while the larger two arms feed a more traditional bar-arm confluence near the co-rotation circle. NGC 1672 is classified as a Seyfert active galactic nuclei powered by accretion via bars feeding supermassive black holes. The energy output of many Seyferts outshines their host galaxies. See *Jenkins et al 2011* for more N1672 details. See S. Díaz-García et al. 2015, *Characterization of galactic bars from 3.6 μm imaging*. Astronomy & Astrophysics. Vol. 587, Article A160.

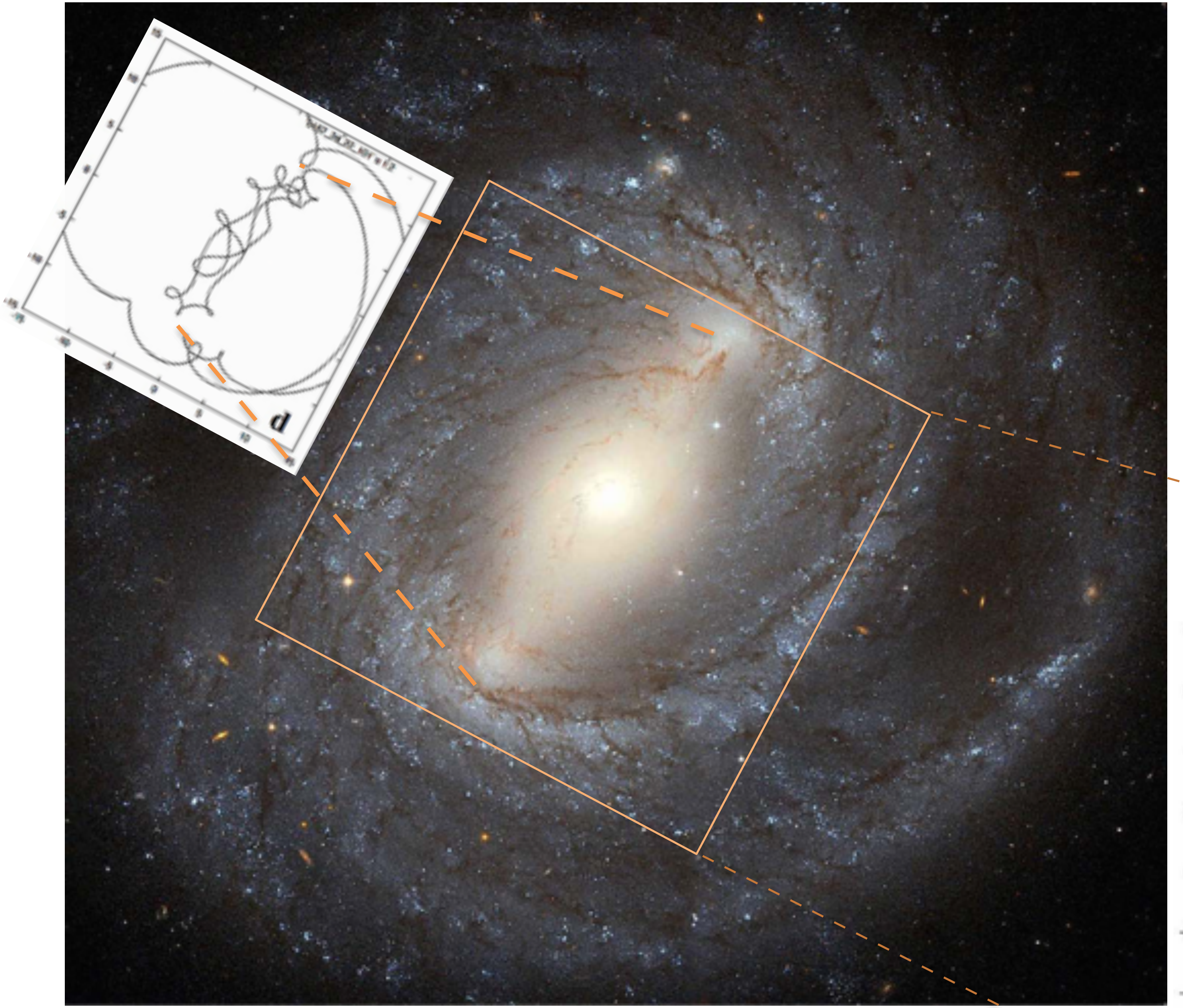


Fig 30: NGC 4394 is a remarkable galaxy in Coma Berenices which is too often overlooked in favour of nearby giant M85. The small spike-like dust feature in the upper bar plus the the two small "bulbs" in the bar-arm confluence indicates that N4394 is undergoing an *ansae* ("wings") phase of early bar formation. When this phase occurs the bar's wobbly box-shaped stellar orbits mix with stable periodic orbits of a the typical elongated x_1 bar families. The small upper left inset shows how wobbly the orbits can be.

Of greater long-term importance are the "banana" resonance families (termed "manifolds" in Lea Athanassoula's many papers). The gas tubes change shape and orientation over the lifetime of the galactic bar cycle. They demonstrate one of the primary purposes of bar cycles in galaxies, diffusing excess angular momentum as virial thermal cooling flow to the outer parts of the galaxy. The process can be thought of as a form of galactic lung system. Images from *Patsis 2006*, *Athanassoula 2012*.

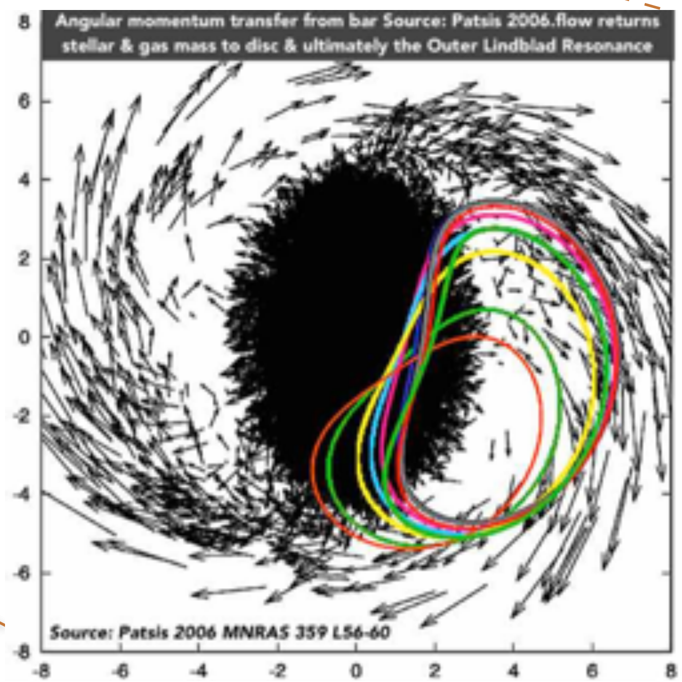
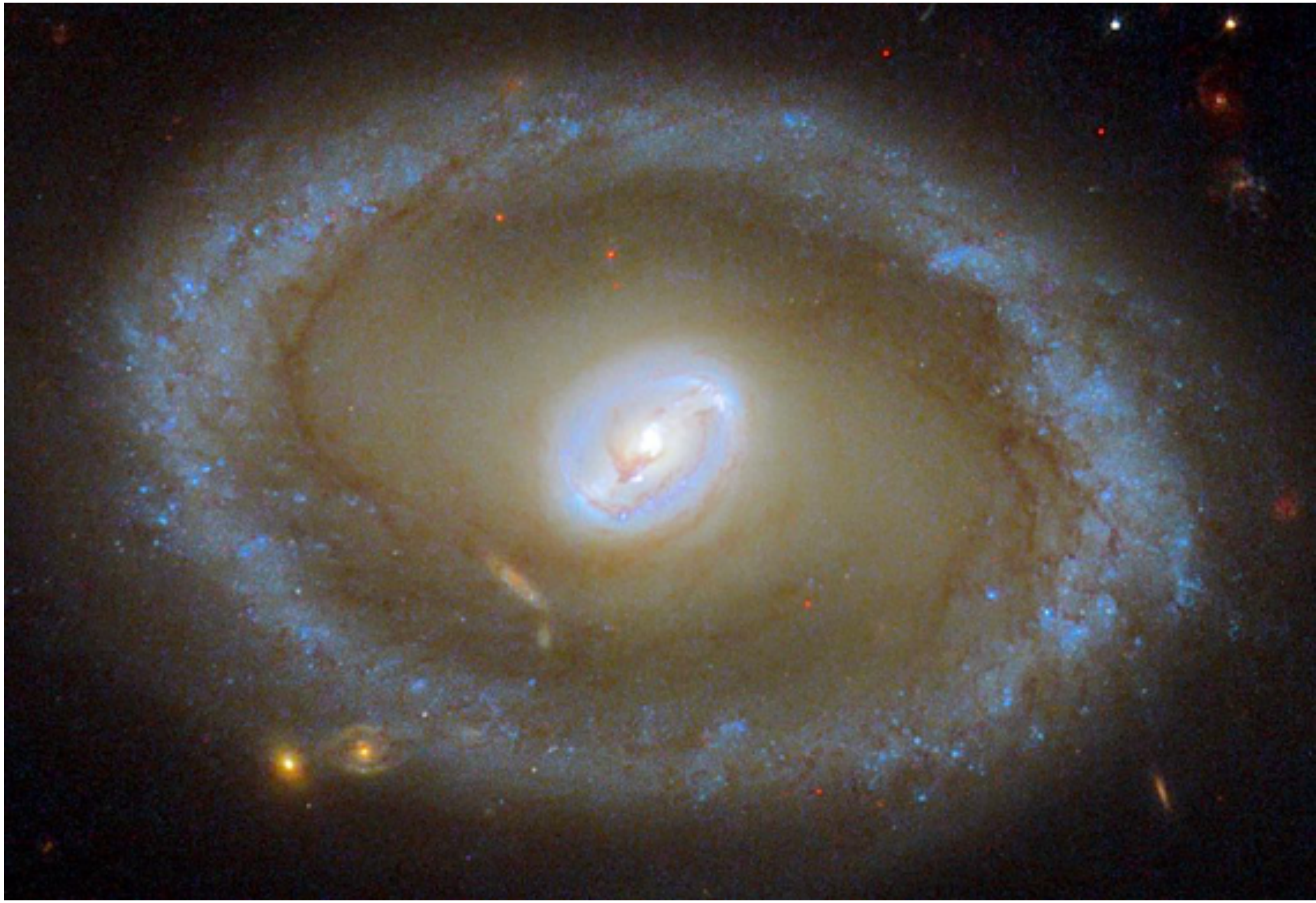
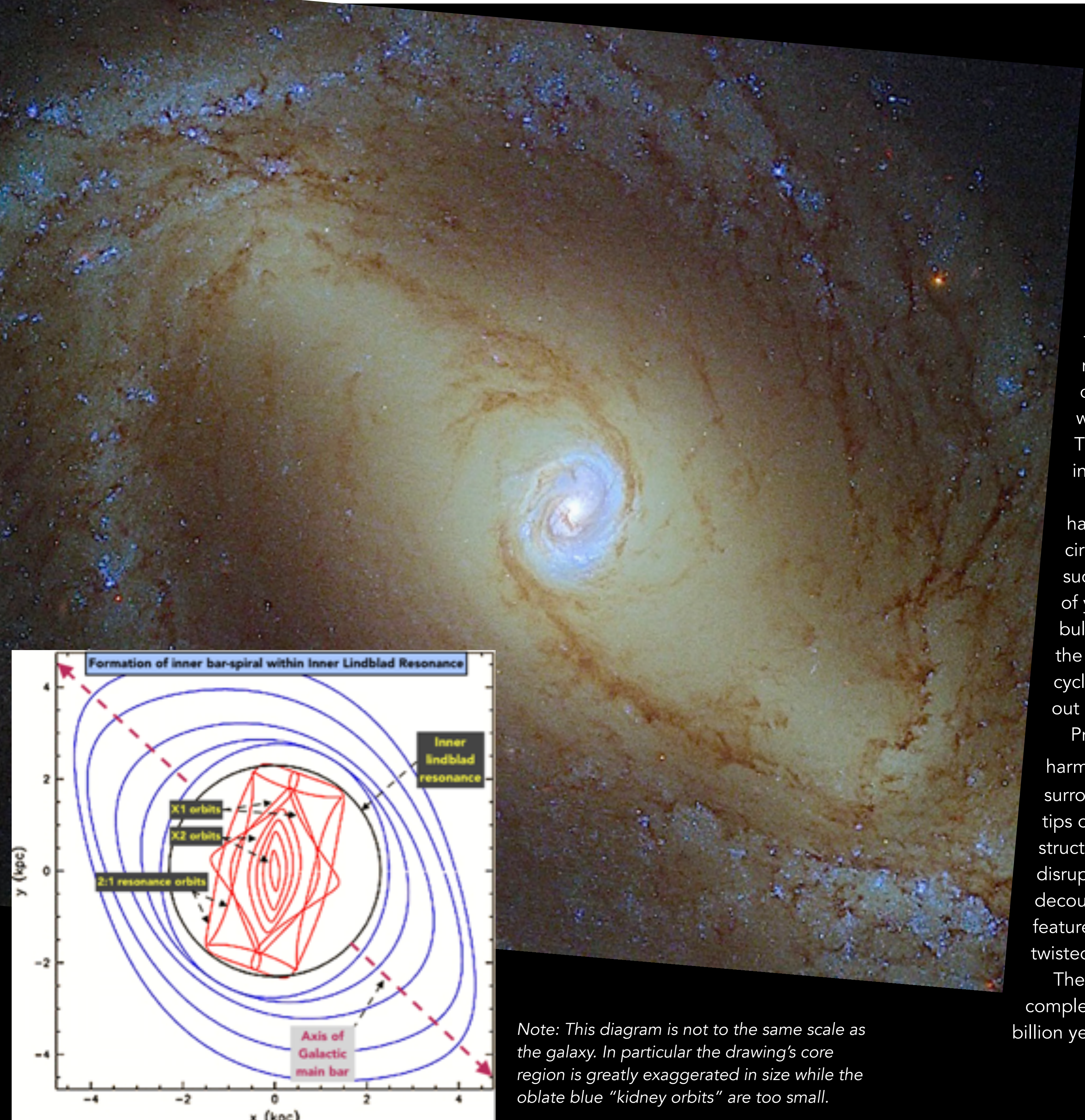


Fig. 31: NGC 3081 in Hydra, some 26.4 Kpc (86 million ly) from us, is a Type II Seyfert galaxy characterised by a dazzling high-energy nucleus powered by an actively accreting supermassive black hole. The dusty centre outlines a inner bar-spiral that evolved outwards from the core from a supernumerary Inner Lindblad Resonance (2ILR). The 2ILR itself evolved from the same core-bar circulatory friction which powered the original bar when the galaxy was a Grand Design spiral. Both ILRs arose from an instability in two sets of gas velocities amplified by resonance at the radius when the two velocities matched and thus reinforced one another. The ring-like periphery of the inner bar and the much larger more distant ring rimming the entire galaxy are both products of co-rotation physics in which the rotational period of the bar is the same as the rotation of the spiral wave and hence self-reinforcing. The inner spiral wave is easily discerned, but the outer spiral wave has been merged into a resonance ring. Large-diameter supernumerary resonance rings are abundant with bright blue young massive clusters <200 Myr old and bursts of new star formation <30 Myr old. So long as its gas reserves last, N3081 will spin up the excess gas in the inner accretion disc and eject it out the poles of the black hole into the halo above. The gas inside the polar jet will eject from the galaxy to high galactic altitudes from which it will return only very slowly over 100-million to half-billion-year time frames. The rest will flow outward via angular momentum to replenish the large outer resonance ring, which explains its present high star-formation rate. The "dead" zone between the two rings is a star-poor, gas-rich region so low-density that remote galaxies shine easily through. The rotational flows in various regions of the galaxy are evident in the streamlines of dust filaments. Note that the dust lanes in the "dead zone" are nearly circular, indicating little inward radial motion. The Hubble Wide Field Planetary Camera 2 (WFPC2) combined ultraviolet, optical, and infrared data to reveal distinctive warm and cold gas features of the galaxy in addition to its energetic star-forming zones. Source: Buta et al.,"*A Hubble Space Telescope Study of Star Formation in the Inner Resonance Ring of NGC 3081*", *A-J* 2014.





Note: This diagram is not to the same scale as the galaxy. In particular the drawing's core region is greatly exaggerated in size while the oblate blue "kidney orbits" are too small.

Fig. 32: Galactic bars are not as serene as their visual smoothness suggest. They are gas and dust, hence they extend and contract in length and thickness in relation to the density of the spiral arms which feed them and the dense bulge which consumes their gas and stellar inflow.

The bulge is the main heat engine of the galaxy. As with any heat source, its excess thermal (kinetic) energy has to go somewhere. Radiation rids the galaxy of the electromagnetic excess (which is not thermal). Much of the kinetic excess goes into making new stars. The rest is transported by the galactic wind of angular momentum transport back into the disc, where it ultimately fills and fuels the outer spiral arms. That is where the young clusters outside our solar circle in the Milky Way get much of their fuel.

As can be seen in the inset, the bulge of NGC 1433 has amassed enough gas to become unstable within the circle of its Inner Lindblad Resonance, initiating a succession of processes that will end hundreds of millions of years from now in a new spiral growing out of the bulge as the old spiral dissipates from mass loss feeding the old bar. The spiral-to-bar-to-bulge gas rejuvenation cycle will slowly progress until the galaxy indeed does run out of gas. That could be several Hubble times from now.

Presently the bulge is undergoing a perturbation in the harmony of its x_1–x_2 orbits and the 2:1 resonance orbits surrounding them. A new short-bar is forming, and from the tips of the short bar we can already see an infant spiral structure developing. The torque and shear forces that disrupt the spiral arm's gas clouds are so strong that they decouple gas from its clouds and stream the gas into a featureless surface dotted occasionally with dust clouds twisted into filamentary shapes.

The Milky Way is thought to have been through two complete cycles of bar growth and dissolution in the last 6 billion years and is amid its third cycle.

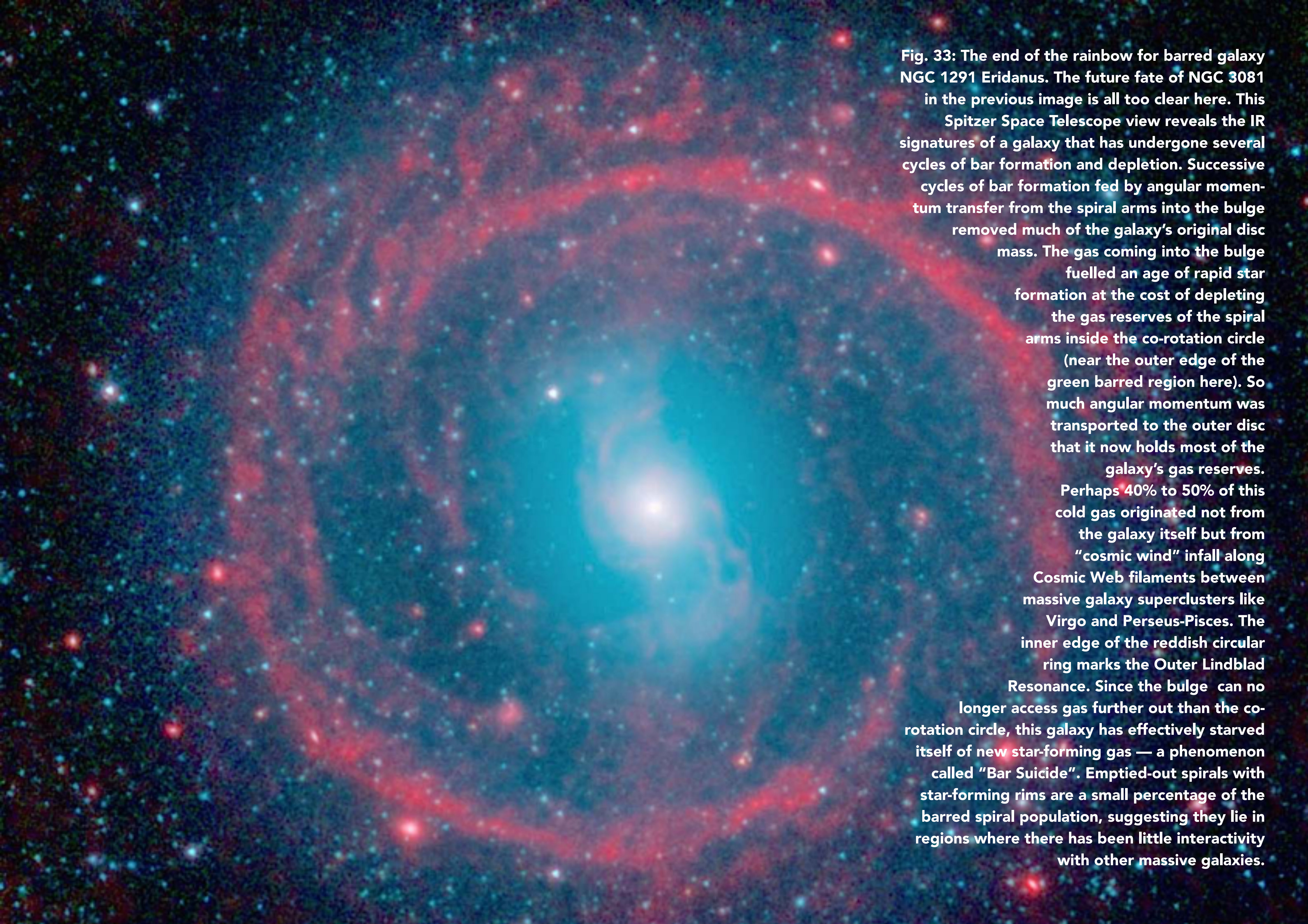


Fig. 33: The end of the rainbow for barred galaxy NGC 1291 Eridanus. The future fate of NGC 3081 in the previous image is all too clear here. This Spitzer Space Telescope view reveals the IR signatures of a galaxy that has undergone several cycles of bar formation and depletion. Successive cycles of bar formation fed by angular momentum transfer from the spiral arms into the bulge removed much of the galaxy's original disc mass. The gas coming into the bulge fuelled an age of rapid star formation at the cost of depleting the gas reserves of the spiral arms inside the co-rotation circle (near the outer edge of the green barred region here). So much angular momentum was transported to the outer disc that it now holds most of the galaxy's gas reserves. Perhaps 40% to 50% of this cold gas originated not from the galaxy itself but from "cosmic wind" infall along Cosmic Web filaments between massive galaxy superclusters like Virgo and Perseus-Pisces. The inner edge of the reddish circular ring marks the Outer Lindblad Resonance. Since the bulge can no longer access gas further out than the co-rotation circle, this galaxy has effectively starved itself of new star-forming gas — a phenomenon called "Bar Suicide". Emptied-out spirals with star-forming rims are a small percentage of the barred spiral population, suggesting they lie in regions where there has been little interactivity with other massive galaxies.

Envoi

There's a certain symphonic quality to the way galaxies are arranged by the laws of angular momentum. It resembles the way harmony on a five-line bar arises out of the laws of vibration on a string. Musical tones can take on a myriad of tonalities and tempos, but they are still bound to those five lines by the physics of vibrating strings.

The dynamics of a galaxy's stars and gas are intertwined with its gas reserve in the same way a melody is intertwined with tones of the staff. The large reserves many galaxies still have left over from their earliest times join with a not-inconsiderable infall of pristine hydrogen arriving along cosmic filaments to keep galaxies going for an unknown number of Hubble times yet to be.

Galactic bars churn the galaxy much the same way an old-time cake mixer churned all the liquid, fat, and powdered ingredients for a batch of muffins. Bars play a critical role in distributing gas to the birth places of the stars, whether the stars are in the bulge or the disc.

Bars are the mixer that regulates the distribution of gas around the galaxy. Instead of muffins we get star formation, bars, bulges, black holes, dust clouds, comets, and those magical moments when we look beyond what we see. Galaxies play second fiddle to no other music. Their melody is eerie and serene at once. It adheres to five sets of physical laws that can be imagined as lines on the universe's musical staff. One is *angular momentum*. *Thermodynamics* is another. A third is *gravity*. A fourth is *hydrodynamic Mach speed* (the speed of a shock wave through its medium). The last, and far from least, is *magnetodynamics*.

These five are the hand on the bow moving the strings of the galactic violin. One finger holds, another one guides, a third one pushes, the fourth one pulls. The thumb holds everything in balance.

A galaxy is music we can see. It is so faint it is almost not there, yet it yields such an incomparable beauty that it alone is reason enough to keep us going.

Set up the scopes, lads, we've got a long night ahead.

Blyde River Canyon by Martin Heigan

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