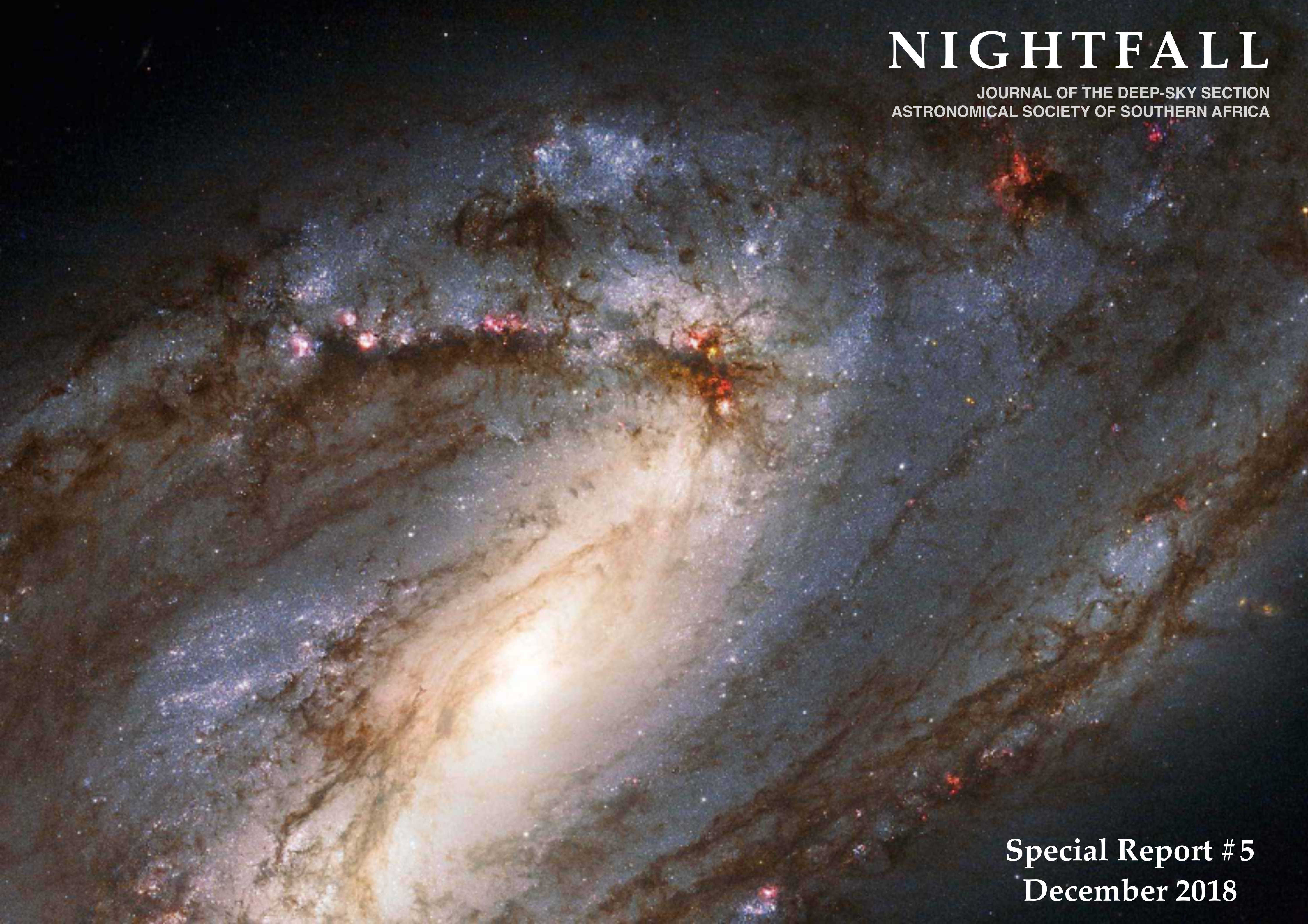

NIGHTFALL

JOURNAL OF THE DEEP-SKY SECTION
ASTRONOMICAL SOCIETY OF SOUTHERN AFRICA

Special Report #5
December 2018

The constellation Aquila, the Eagle, by Johann Hevelius 1679. Courtesy of Barry Lawrence Ruderman Antique Maps

NIGHTFALL

Astronomical Society of Southern Africa
Vol. 3 ISSUE #1 January 2018

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Published December 2018
Astronomical Society of Southern Africa.
Observatory, Cape Town, South Africa
Editorial address: https://assa.saao.ac.za/
Website: http://assa.saao.ac.za/sections/deep-sky/nightfall/

Print-on-demand editions produced by Atelier Books LLC
Postnet 18, Private Bag X1672
Grahamstown 6140, South Africa
email: assa.nightfall@gmail.com

ISSN 2617-7331

The winds of change are blowing over Aquila – I

NGC 6749, Demure, Dwindling, and Doomed

Douglas Bullis

NGC 6749 Aquila has a reputation as the most difficult NGC object in the sky. The observing reports one finds on CN involve 300mm and upward (way upward) scopes. I wondered about its visibility in my 150mm to 200mm medium-aperture scopes. Now I've observed its field across the past three nights for more than an hour each night under excellent skies using 100mm to the 200mm scopes.

There are two issues in positively distinguishing N6749 from adjacent field contamination. First, listed globular visual magnitudes in most charts are misleading. Globular light falls off at a specific exponential rate from core to halo which depends on the cluster's density, from Class I highly concentrated, through Class XII, very loose. A better measure is the half-light radius which is a measure of core concentration. You can look up this data and all the other relevant data in the Harris Catalog. After checking what I can actually see against what's listed in Harris, the half-light radius is the only visibility criteria I use now .

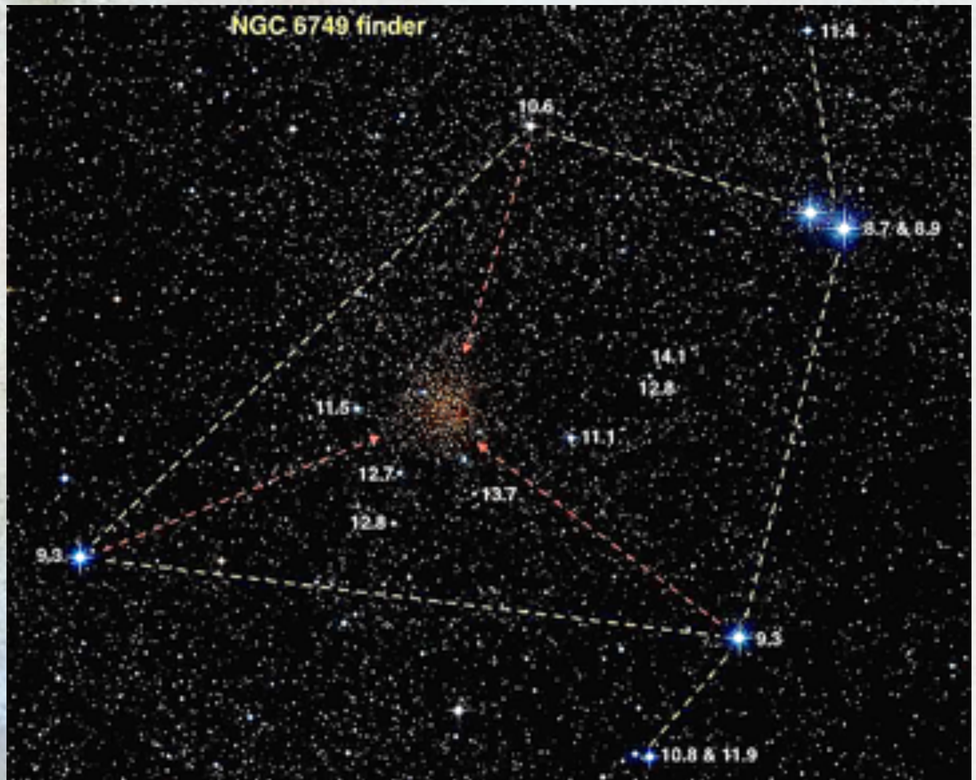

Fig. 1: The star pair HD 177420 & 177439 (upper right) are a convenient starting point on a NGC 6479 search. The cluster's listed M_V 12.4 is misleading. Its half-light radius 1.1 arcmin and core surface brightness of 21.2 mag arcsec^{-1} are more accurate indicators of see-ability.

N6749's half-light radius is 1.10 arcmin across a total diameter of 6.1 arcmin. That indicates a very weak halo concentration and low core visibility. The visual mag in N6749's half-light radius is 11.9. N6749 is the loosest globular in the sky at Cl XII, with a mean surface brightness of 21.8 averaged across the cluster's listed diameter.

Problem #2 is that when using 150mm to 250mm scopes there is an asterism of seven mag 11.8 to 14.2 stars in a roughly trapezoidal shape directly adjacent to N6749. This group abuts N6749 out to 5 arcmin W and 2 arcmin SW. In a 150mm scope and sub-200x magnifications the trapezoidal group blends into a hazy patch which can easily be mistaken for N6749. My 200mm Mak at 169x quickly resolves the 7-star distraction into distinct stars which are then easy to ignore. Only then does N6749 become visible as a very faint glow just touching the NE corner.

It took nearly an hour to confirm the cluster on first night out under approx. mag 6 seeing, and that was only three firm emergences.

As is often the case, once having cleanly ID'd the object, it is much easier on subsequent tries. Now I visit the cluster regularly during its meridian passages June through August. N6749 shows irregularly emerges as a 1.5 arcmin very faint glow in my 180mm Mak-Cass.

No easy-pleasey for the big boys, either

It may gratify those who try it but don't spot it that professional astronomers face the same problem: it's tough to distinguish cluster glow from the rich, crowded field it's in. N6749 is entering a rough crossing through the Milky Way arm-bar merge, a region dense with stars nearly the same visual properties as the cluster.

Further research reveals N6749 to be a distant fossil halo cluster undergoing what may be a final disruptive pass through a turbulent interarm region near the point where the MW bar turns sharply to the left to become the Sagittarius Arm. The cluster's light path to us traverses 25,750 light years, of which nearly half is through a dense, turbulent star-forming region where the Sagg Arm joins the MW bar at 90° perpendicular. N6749 has only 1975 solar luminosities of stars left and is a case study in what happens when a globular is absorbed into our galaxy. The Milky Way disc has disposed of roughly 250 globulars in the last 11 billion years; the present population is approx 23% of the calculated original populace. Many of those disruptees ended in the outer halo. N6749 may soon join them.

For all its interest to astronomy enthusiasts, N6749 is little studied by the professionals these days. A literature search on ADS and a few papers, the most recent from *Rosino et al 1997*. *Brian Skiff's 2002* paper reviewing Mira variables in N6749 was the last paper published on this cluster to date. Simbad lists *109 citations*.* The amateur astronomer's thriller is a professional astronomer's sleeper.

A pity, because N6749 is anything but a staid, boring cluster. It is about to endure one of the most interesting and fraught fates a star cluster can endure: a disc crossing through one of the worst places in the galaxy to try it. N6749 is an old halo globular nearing the Scutum Star Cloud — bad enough in its own right, but all the worse because the Scutum Cloud is also the place where the Milky Way's spiral arm system takes an abrupt 90° swerve into the Galactic bar. (Part III of this report will go into the wild & wondrous domaine of galactic bars.)

No kinematic parameters have been published for N6749. A review of GAIA data at N6749's galactic coordinates 036.20016, –02.2053 don't indicate whether the passage is grazing or a fast plunge. We do know that N6749 has an extended blue horizontal branch and a blueish main-sequence turnoff point where hydrogen fusion transfers from core burning to shell burning surrounding the inert helium core. This is the turnoff where the star cools and reddens as it moves roghtward towards the red giant slope.

N6749 is the loosest globular in the sky, a Class XII, from which a disc crossing can *tidally strip a substantial portion of its outer stars* into the bulge if the galactic potential exceeds its binding energy.

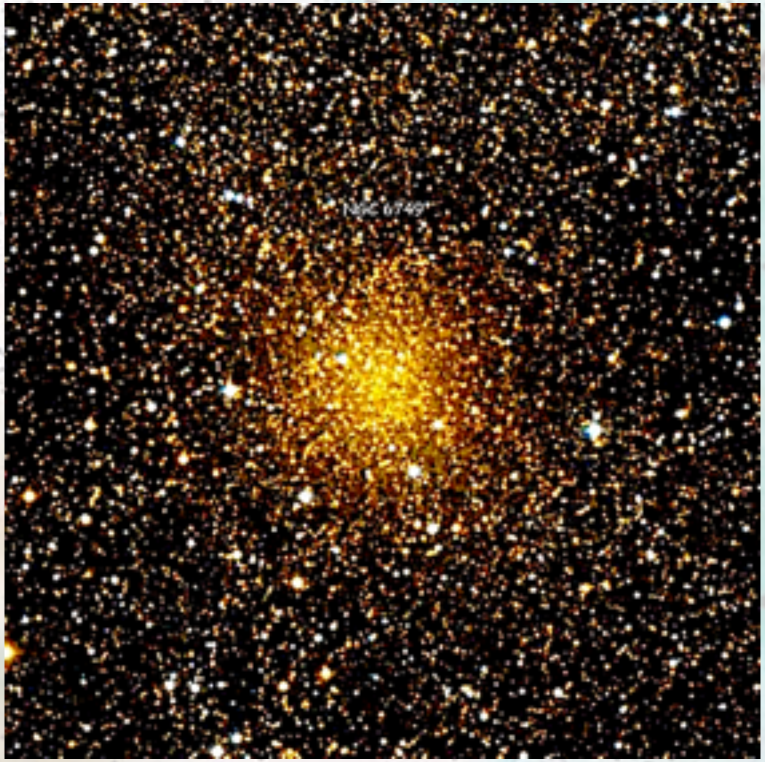

Fig. 2: John Herschel discovered this globular cluster during his observations from Bath in Southern England in 1827. It is a perennial favourite of amateurs because of its difficulty. The ubiquity of same-magnitude field stars make defining the cluster stars hard to distinguish from field noise.

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* The annual "Most Improbable Paper Award" for 2016 surely would have gone to "*Globular clusters as cradles of life and advanced civilizations*", which concluded, "Civilizations residing in globular clusters could therefore, in a sense, be immortal." It is actually a serious piece that appeared in *The Astrophysical Journal.*

NGC 6749 is considerably reddened by galactic dust, a fact quickly suspected the first time we see it. An undimmed globular of N6749's size such as M53 high in the halo glows considerably brighter at nearly the same diameter. We see only a fraction of the light we would see if N6749 was a few kpc further above the disc. Quite a number of other disc globulars suffer this same umbrage — NGC 6526 Sco, 6532 Ara, 6366 Oph, xx Libra (not for nothing dubbed 'the Ghost' by its fans), M56 Lyra. It's a long list, all the more fun because the clusters are so shy.

The [Fe/H] metallicity of N6749's blue horizontal branch (BHB) has been variously estimated between –1.65 to –0.97, which comes to roughly 3% to 22% of the Sun's (by definition zero). The uncertainty comes in part because the BHB lies at mag 19.7 and the main sequence turnoff (MSTO) at 23.4. Accurate photometry at these levels requires four-metre-class optics and sophisticated equipment, e.g. the MegaCam mounted on the 3.6-m Canada-France-Hawaii Telescope (CFHT). To get an idea of what it takes to work with an observatory photometer, *here's a page from the MegaCam manual*.

The standard for reliable globular photometry requires the telescope system to reach at least 1 magnitude below MSTO. MegaCam-class equipment is not for the faint of budget. Given that it takes time to collect flats and darks using special panels inside the observatory dome, plus perhaps ten 30-second images of each radial annulus (usually 3) at perhaps $20,000 per hour, one can understand the dearth of N6749 studies in recent years.

So we press on with what we have and make the best of it. N6749's blue horizontal branch (BHB) is notably metal-poor. Its E{B — K band) reddening is 1.39 (i.e., 28% of its light is absorbed on the way to us). The cluster's reddening and BHB magnitude allow astronomers to calculate its distance from the Sun as 7.3 kpc (23,800 lyr) . Its Galactic Z coordinate (distance above/below the disc) is 300 pc (980 lyr).

While those numbers are interesting to visual observers, the number that's important to us is the time frame during which N6749 plunges through the Galactic disc. N6749 is a halo globular cluster on a high-speed trajectory through the MW disc at 56 km s^{-1}. N6749's velocity will carry it through the disc plane in about 5.37 million years. For about 1.5 million years before it

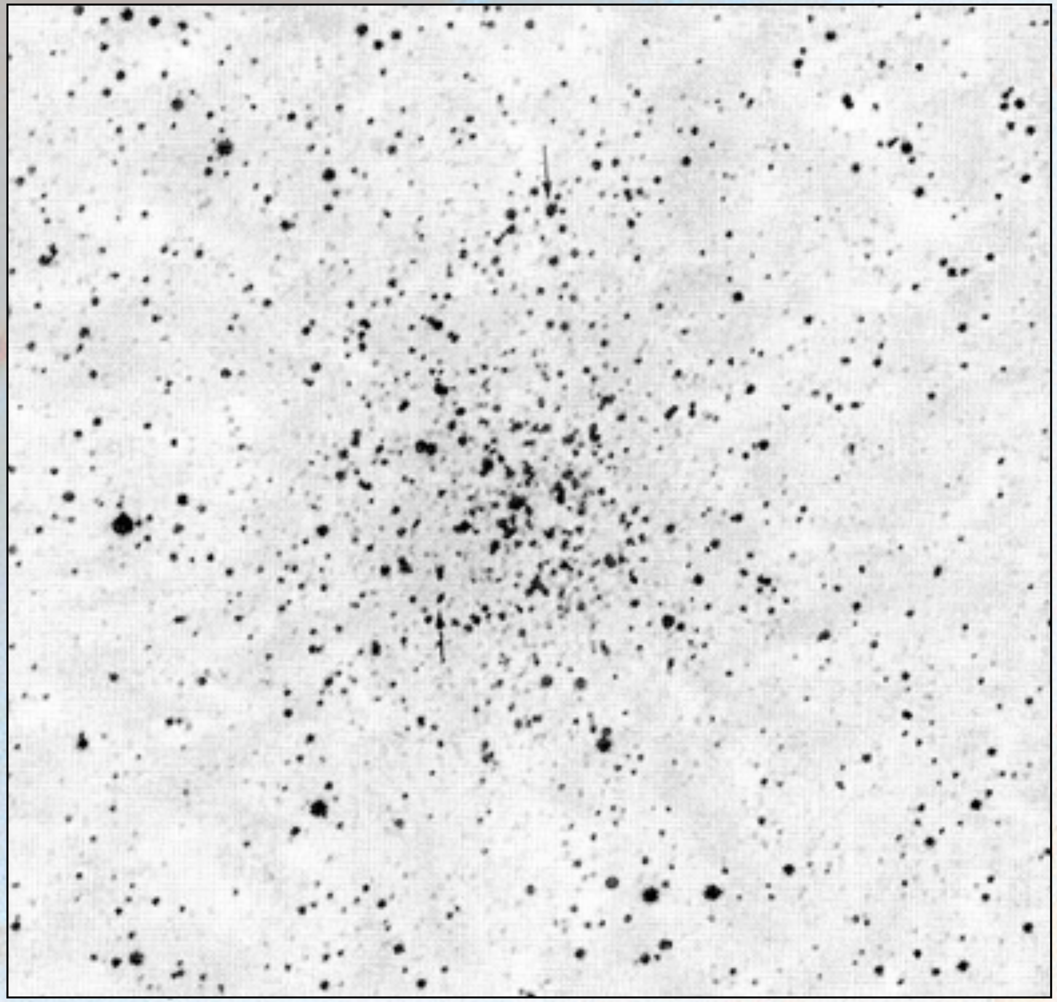


Fig. 3: NGC 6749 imaged down to mag 21.5 in the 3.55 metre New Technology Telescope (NTT) at the ESO La Silla Paranal observatory in Chile. The image covers 2.2 arcmin on each side. The two arrows identify the two mag 19.7 RR Lyra stars used to measure the cluster's reddening at 1.5 mag and distance of 7.3 kpc (23,800 lyr).

arrives at the actual disc plane, it will be moving through increasingly dense and violent thin disc. The thin disc is a maelstrom of high-velocity shock fronts (e.g., Mach 5 to 90), the river-like Galactic magnetic ß-field of ±3.5 Gauss, gravitational over-and underdensities due to star clusters, and giant molecular clouds. GMCs have typical masses of 1 to 10 million $M_\odot$ in an irregular volume from 50 to 300 lyr in cross-section. Star clusters have masses from the low hundreds to high thousands of $M_\odot$. It's Heavyweight versus Flyweight and guess who wins.

The arrival of a galactic bar in a given spiral arm complicates an already tumultuous situation. The story of bars will be told in Part III of this series. For now *this simulation* will convey the physics of near-pandemonium that comprises daily reality in a spiral galaxy. (Download the *MPEG version*, the gif is stuttery.) It's a good thing for everyone that Galactic days are many millions of times slower than shown in the simulation, which can compress between 1 and 20 million years into one video second.

The dynamics of galactic bar-arm confluences are complex and violent. The bar precesses through an arm somewhat faster than the arm rotates. The net effect is to redirect almost all the mass of the bar-arm confluence along the length of the bar. Gaseous matter rotates in elliptical orbits along the bar. Some is captured by the bulge, where it feeds enough gas into the core to form the most massive young clusters in the galaxy, e.g., Arches and Quintuplet in the Milky Way.

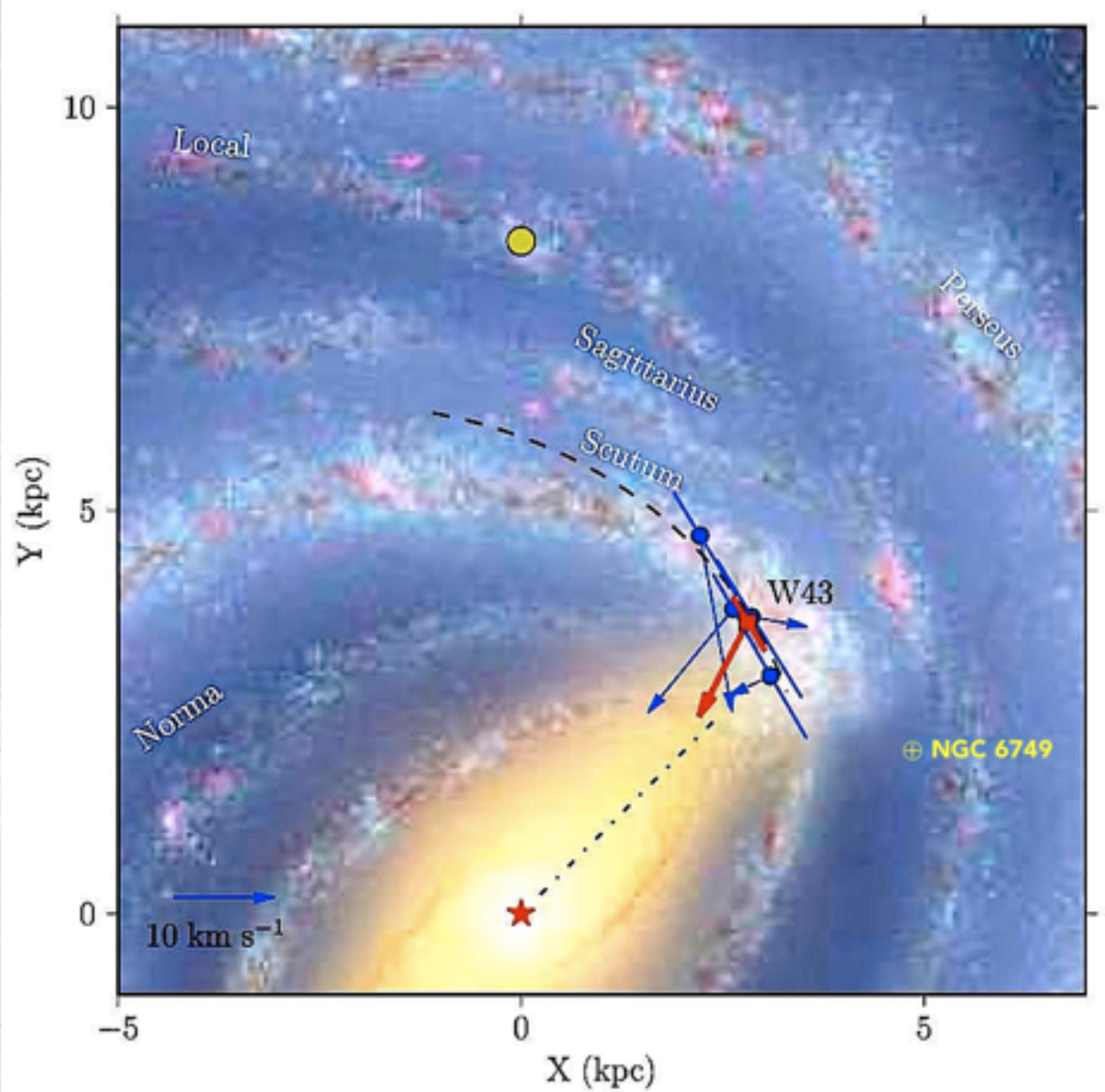


Fig. 4: The blue arrows in this image show four typical vectors of small parcels of matter on paths induced by the chaos of a bar-arm confluence. A shear stress tensor (red arrow) exerts a common force on the individual parcel vectors. Over time, the individual vectors will unify into a flow along the shear tensor. Enormous energy is consumed and redistributed by a shear stress tensor (see Part III). The result is a gigantic swerve involving the entire mass of the bar-arm confluence. If the Solar System was amid that mess, we might not be here to enjoy the show.

Dusty molecular clouds tend to end up on the leading edge of the bar into which the dust's spiral arm flows. Many images of barred spirals show dust clouds threading along the fronts of their bars. Other gas crosses to the opposite bar-arm confluence (Norma in our case), where it exits in a messy spew spilling in both directions along the Norma bar-arm confluence. The countervailing flow from Norma will do the same as it arrives in Scutum.

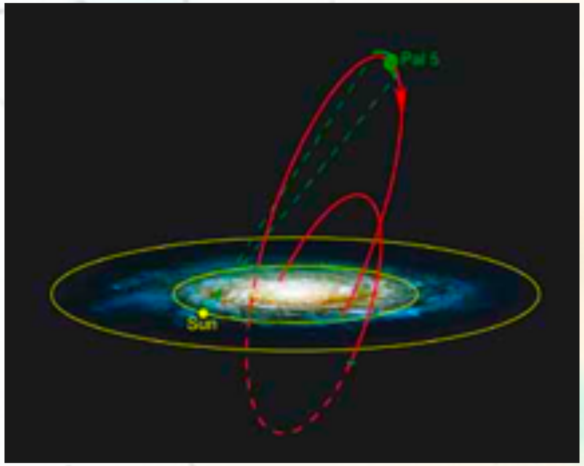
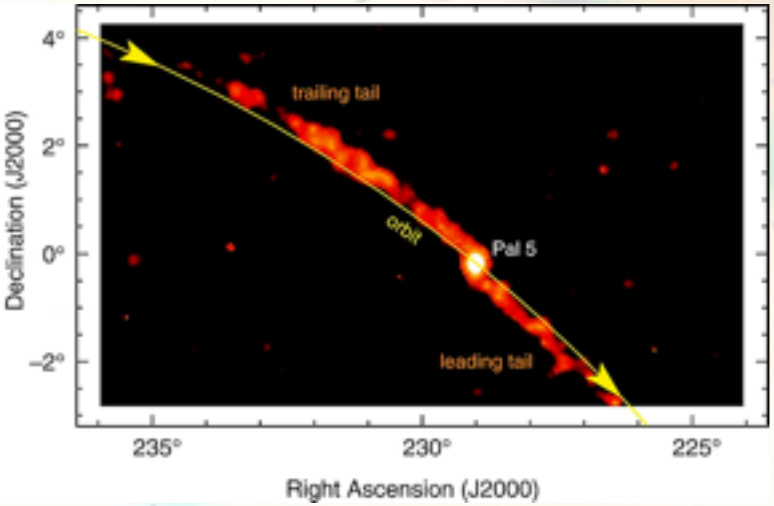


Fig. 5: NGC 6749's actual path to destruction hasn't been mapped. The nearest analogue is Palomar 5 (Oph) which has been cited numerous times as a case of Galactic cannibalisation. This image shows the slender S-shape of fore-&-aft slipstreaming as predicted in N-body sims and observationally in this 2003 SDSS-derived image analysed by Michael Odenkirchen and Eva Grebel et al 2003. A video of the sim is available here.



Globular cannibalisation

It takes billions of years for a galaxy like the Milky Way to chew up a globular cluster. Astronomers haven't completely documented the end-to-end dissolution of a globular cluster, but they have produced some vivid *simulations of the process*. In field studies, *NGC 2298 in Canis Major* has lost an estimated *73% – 85%* of its original stars; it now stands at 7400 $M_\odot$. (See Fig. 1 in *DeMarchi 2006* see how they arrive at these totals.) Another example, Pal 5 in Oph (left) has been tidally slipstreamed so picturesquely that it features regularly in astronomy textbooks.

The mechanics of globular cluster dissolution are fairly well understood because of examples like Pal 15 and 13, NGC 5053 in Coma, and *six of the 43 globulars in the Galactic Bulge*. Halo globulars orbiting through a galaxy disc suffer mass loss from tidal stripping as the globular's outer stars are pulled out of the cluster's tidal radius by the large galaxy's gravity. Across the span of a Hubble time (13.8 Gyr, the age of the universe) nearby galaxies have lost *45% to >70%* of their globular cluster populations.

Low-density Class XI and XII globulars like NGC 6749 Aquila, 7492 Aquarius, NGC 5466–5053 Böötes-Coma, and M55 in Sagg look so airy in our eyepieces because of two self-reinforcing cycles. One, they lose outer stars to tidal stripping when they pass through the dense disc of their galaxy. Two, as their core stars age they lose mass because the mass escapes in the form of electromagnetic radiation. A globular with a central concentration of $c = <0.8$ that enters a galactic disc will lose stellar mass to the galaxy. N6749's core concentration is 0.79.

Globulars like NGC 6749 that spend most of their time in the Galactic halo selectively segregate their stars by mass from the centre outwards. The big stars of ±1 $M_\odot$ and binaries sink to the middle; the littles ones down to 0.08 $M_\odot$ drift to the outskirts. Any brush with galactic tides removes the outer stars first. NGC 6749 hasn't yet begun to show the stress of tidal disruption during its present approach, it is still on the outskirts of the Galactic disc.

Read how astronomers know all this *here*.

The winds of change are blowing over Aquila – II

Fig. 6: W43 nebular complex Aquila. Composite three-colour Herschel image of the W43 molecular cloud complex. The blue 70 μm component traces H II and photon-dominated regions, while earlier stage star-forming cores and filaments are traced by the red component at 250 μm. The W43 star-forming regions of this article comprises the two bright orange-pink clumps at the centre and right centre of this image. *Source*: Nguyen-Luong 2013.

W43: Canary in the coal mine

When we pull out the charts to dream up the evening's goodies, as we look at the Aquila–Scutum region we jot down NGC 6760, 6749, the prettily resolved 6712, the M11 Wild Duck. Maybe M26 too. And oh yes, all those inky dark patches.

Yet completely unknown to us there is an invisible double-Orion Nebula right in the middle of those objects. Called Westerhout 43 after the Dutch-American astronomer Gart Westerhout, who in the mid-1950s made a catalog of hot infrared star-forming regions hidden by the dust in the Galactic plane. If there wasn't any dust, W43 would be bigger, brighter, and more complex than the Orion Nebula.

In the detailed image on the opposite page, W43 is the two smallish clumps within a giant molecular cloud in the early stages of star formation. Unless disturbed by external forces, giant molecular clouds (GMCs) form and dissipate in the Galactic disc in cycles averaging 10 to 20 million years. GMCs weigh in at 5 to 10 million solar masses ($M_\odot$) and 100 to 300 light years in diameter. The word 'diameter' does not imply spherical bubbles drifting in space. Instead, GMCs are contiguous blobs of dense cores congealing along filamentary structures shaped by the Galaxy's spiral arms' magnetic ß-field.

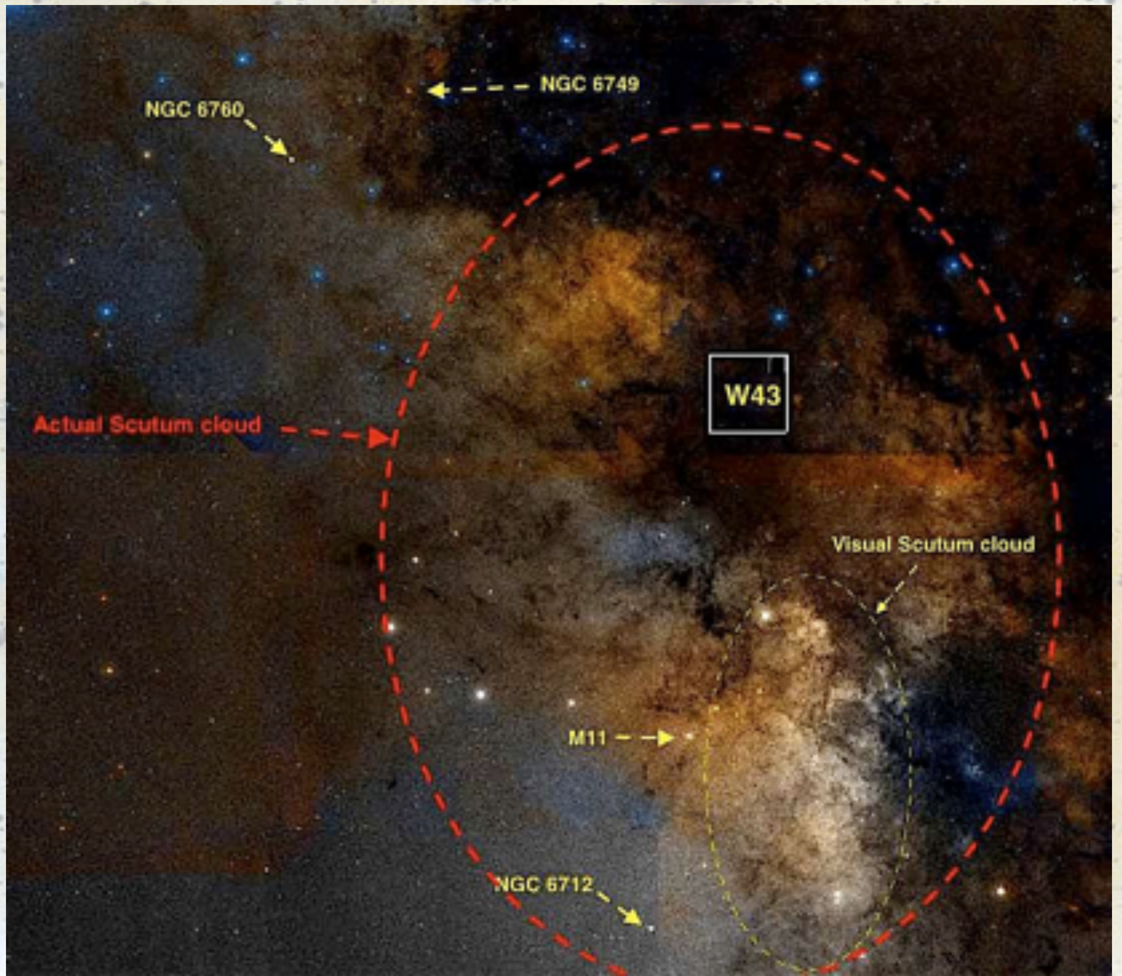


Fig. 7: W43 is visually concealed by Galactic extinction. Wikisky's DSS image seen here suggests a massive, dense gas/dust cloud overlying the position of W43 (square box). W43 itself is only a small portion of the large blob surrounding the box. Indeed, W43 is only the two bright clumps near the middle of the leading page of this article. When a dark cloud is dense enough to completely extinguish starlight from behind it, as we see here, its density is upward of 10,000 gas particles per cm^{-3}.

Assuming that typical gas/dust conditions prevail in this cloud, there will be 10 dust particles in the same cubic centimetre. The vast volumes of space occupied by a molecular cloud produce total extinction at optical wavelengths.

W43 is a *cloud-collision* stellar nursery, one of two main *mechanisms of star cluster formation*. (The Trifid Nebula M20 is also a cloud-collision cluster, see below.)

The commonest type of *cluster formation* in galactic discs is the *collect-and-collapse* (C&C) scenario. In C&C clouds, a giant molecular cloud contracts inward when its molecular density approaches 10,000 H_2 molecules cm^{-3}. It is not easy for them to form stars. They are as delicate and wobbly as soap bubbles blown by children. In a cloud 300 light years in diameter in a place as fractious and gusty as a galaxy disc, mass-density and velocity shears stress the bubble-like gas clouds from multiple sides. The original roundish ball fractionates into clumps whose densities reach 100,000 molecules cm^{-3}. Those in turn collapse into even denser regions, called cores. When cores reach 1 million H_2 atoms cm^{-3}, the magnetic and turbulent forces which resist gravitation weaken. Rapid collapse into star clusters ensues. 'Rapid' can mean 100,000 to 2 million years depending on the cloud's density distribution.

The other star formation mechanism is *cloud-cloud collision*. These can range from grazing ricochets that squeeze out small low-mass clusters usually planar in shape rather than round, to direct hits at high velocities, e.g., 20 km sec^{-1} in the case of the mechanism that made the M20 Trifid. The Trifid is a *cloud-cloud collision product*, The component clouds were ~3,000 $M_\odot$ each and collided at ~12 km s^{-1} (26,900 mph). Today, one star cluster and one million years later, the clouds are 1 and 2 parsecs on either side of the familiar tri-lobed cloud complex and drifting apart at 8 km s^{-1}. The M20 gas/stellar complex we see visually weighs in at 2700 $M_\odot$ of leftover gas and ~532 $M_\odot$ of stars. This is less than a tenth of the mass needed to bind the system, so the Trifid will inexorably diffuse into the galaxy's disc. (More details *here*.)

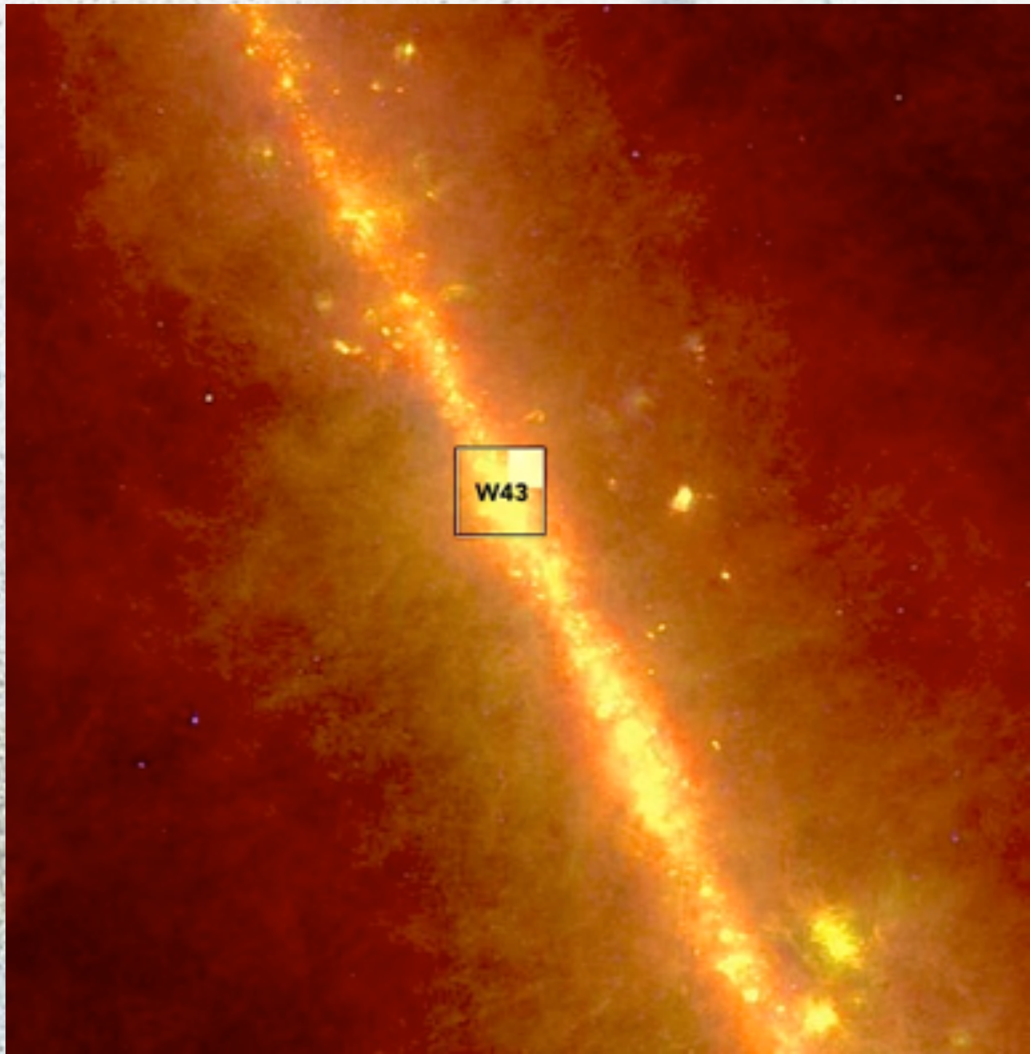


Fig. 8: Imaging W43 in near infrared (NIR) cuts through the disc opacity to reveal W43 as part of a vast network of hot spots in the Milky Way's 100 light year wide thin disc. This IRAS Infrared Sky Survey map reveals the region to be a giant 8000 to 20,000 K emission complex bathing the Scutum Cloud with a thick haze of orange-red Hα and H_2 emission. W43's visual bands are extinguished by dust, but they radiate strongly in the H_1 21cm radio band, the 8μm and 870 μm continuum of ^{12}CO 2-1 & 3-2, and ^{13}CO 1-0 electron shell transitions in atomic and ionized carbon. W43 also radiates strongly in the infrared and X-ray bands. (You can read more about how this works in the *arXiv* and *ADS* data pipelines.)

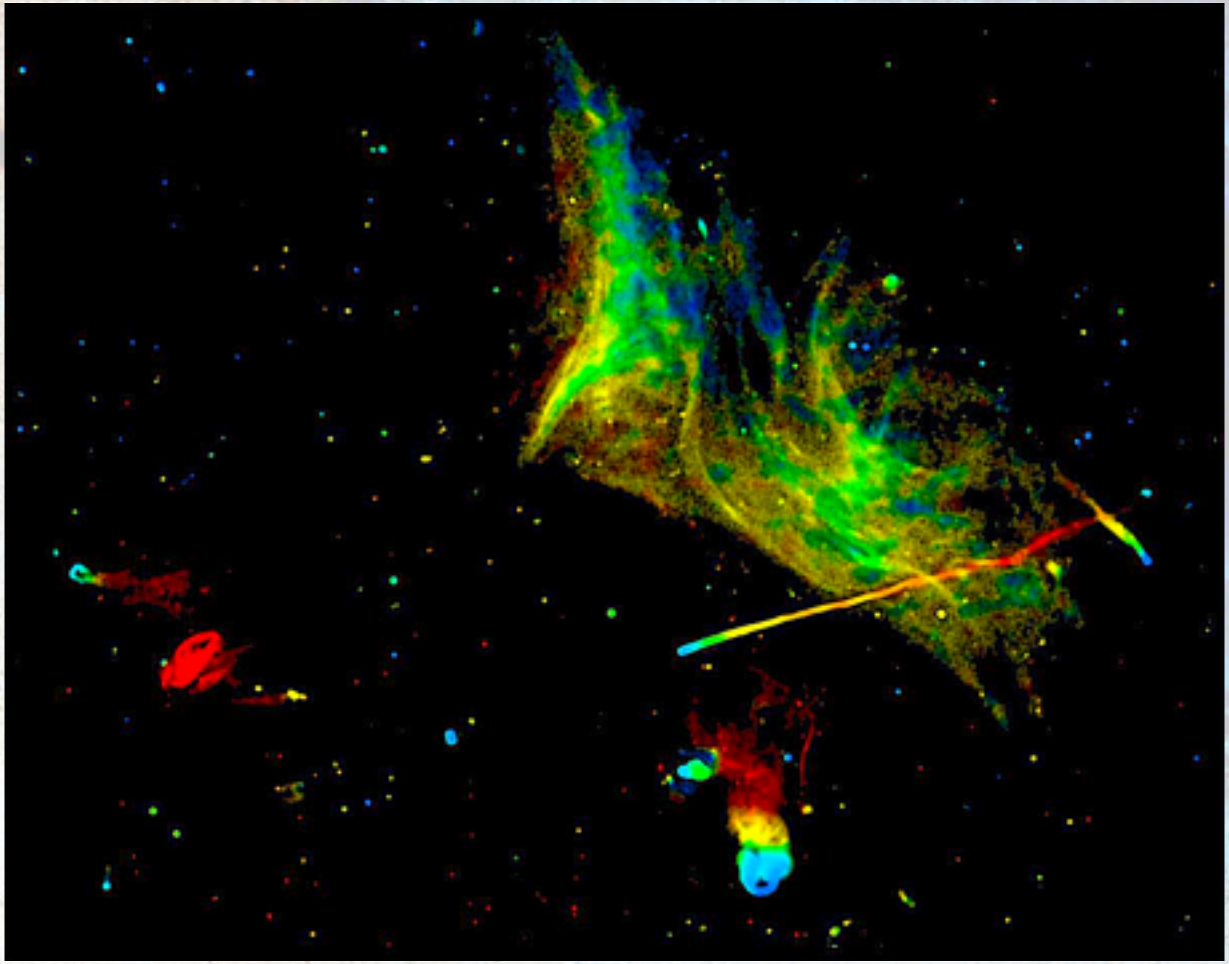


Fig. 9: At the very low-temperature (1–3 K) regime of HI atomic hydrogen energies the W43 region might look something like Abell 2256, here recorded in the Jansky VLA in New Mexico using three radio bands. The bands have been artificially coloured using standards we are accustomed to seeing in the optical. Blue is the highest frequency and thus more energy-dense, orange-red is in the 408 GHz band and the least energetic per square metre. The threadlike feature is a pulsar jet that excites very low density hydrogen. Source: National Radio Astronomy Observatory (NRAO).

The Scutum Complex is a large, massive stellar nursery filled with stars, star clusters, diffuse atomic gas, low- to medium-density atomic gas, high-density molecular gas, and frightful quantities of UV radiation. Big as it is, W43 is just a face in the crowd of a very large city. At its very beginning it was a very large cloud of atomic hydrogen, each atom of which was separated from the others by as much as one per cubic metre. Embedded in the gas was a tiny fraction of dust. The presence of dust was critical, for two reasons.

First, the dust particles captured tiny amount of photon energy, very gradually raising the temperature of the dust, e.g., from 2–3 K to 5-10 K, but conversely cooling the cloud because the absorbed photons could no long excite the hydrogen's electrons. Being cooler the cloud contracted, increasing its central density. This was a self-enhancing process.

Second, interstellar dust comes in two basic types: carbonaceous rings, and aliphatic silicate grains. 'Aliphatic' means atoms connected in chains, not in rings as in the case of carbon. Carbon rings have a rather greasy character — stuff sticks to them.* As W43's dust warmed past 18K it would have slowly accumulate hydrogen atoms on the dust's surface.

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* Sci-fi warp speeds have problems not just with Einstein, but also with Galactic filling station attendants. Have you ever cleaned off the bugs on the windshield after a night drive in the middle of summer? A space ship traveling at warp velocity will impact an enormous number of carbonaceous dust particles, which would smear all over the starship. By the time the Millennium Falcon got to Altair 4 or whatever, its windows would be so smeary the crew wouldn't be able to see the loading dock. The Millennium Falcon's window problem would be much worse. At relativistic velocities the carbon dust would bond with the surface atoms of the windows, rendering them permanently opaque. Space dust us basically space gunk. The Millennium Falcon would arrive permanently black, not gleaming.

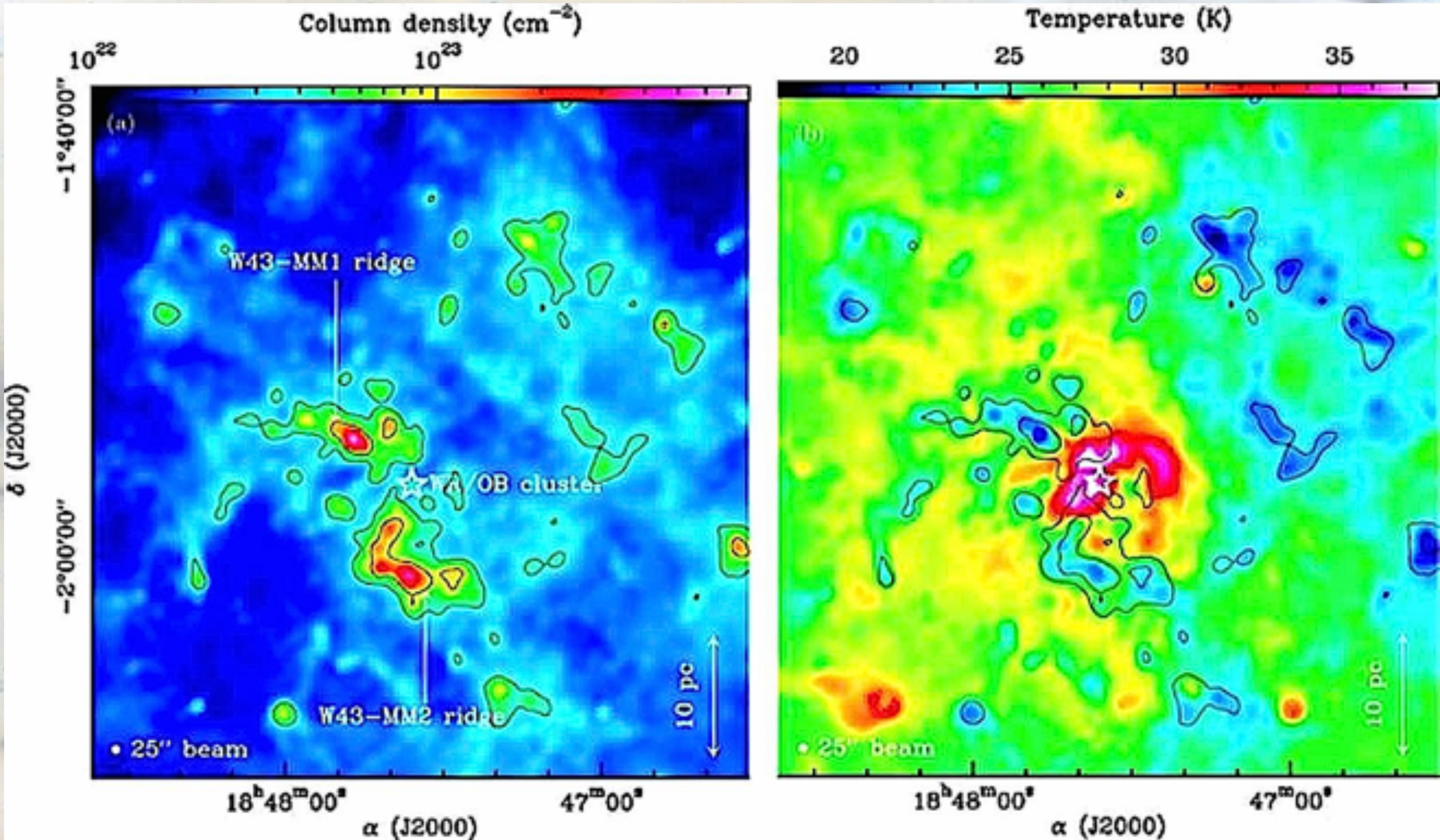


Fig. 10: W43 in IR. Panel (a) is the gas column density (colour and contours), and panel (b) is the dust temperature (colour) and column density (contours) derived from Herschel images. The black contours are the 4 x 10^{22} cm^{-2} and 1 x 10^{23} cm^{-2} levels, outlining the W43-MM1 and W43-MM2 ridges and their immediate surroundings. MM1 and MM2 are the hottest parts of W43; each has more stars than the Orion Nebula. The MM1 ridge has 21,000 M$_\odot$ of HII gas; MM2 has 35,000 M$_\odot$. (Divide by 20 to get a rough idea of how many stars can form in these.) The star symbol in image (a) is a Wolf-Rayet /OB star cluster responsible for the giant HII region seen as the hot red bubble in (b); it has 9800 M$_\odot$ of star-forming gas. Only about 5% of a gas reservoir in a clump as dense as W43 will actually end up in stars; the rest will dissipate back into the local medium to have another go at making a cluster some day 110 million years in the future when the present contents of the Scutum-Sagg Arm rotates around to slide into the Perseus Arm. The star symbol in the image identifies the Wolf-Rayet/OB star cluster responsible for the giant H II region seen in panel (b). *Source*: *Nguyen-Luong 2013 apj481525f2*. Further reading *here*.

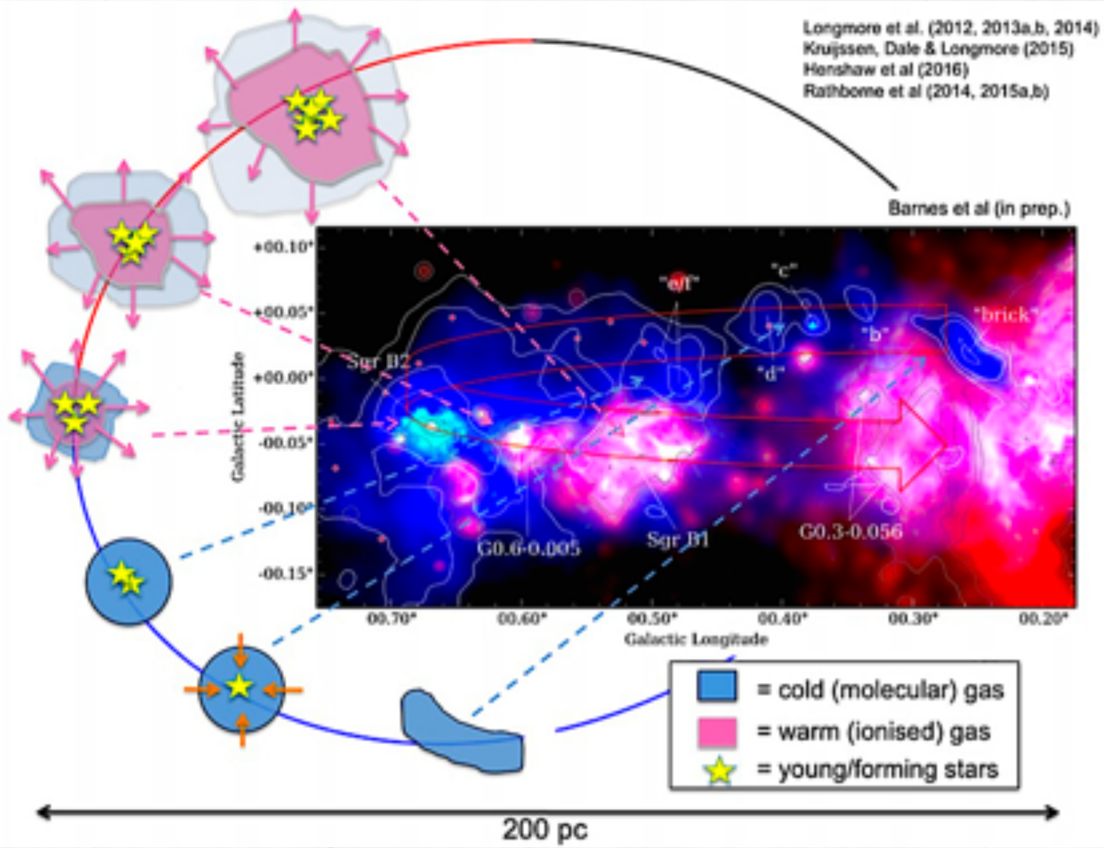


Fig. 11: The inset in the above image shows observations of the cold molecular gas (blue), and hot ionised gas (red) towards a region within the inner ~100 pc of our Galaxy. This region contains the four most massive and compact (all $M > 10^5 M_\odot$) gas clouds in the Galaxy, names the Brick, and Clouds D, E, and F. These clouds are links in a chain along a coherent gas stream known to be a dust ridge (horizontal across the centre of the image). In the red emission clump on the right side there are very few signs of active star formation. The blue-coloured patches on the left side show increasing signs of star formation, until there is significant star formation in the protocluster B2. At present the Aquila cloud W43 occupies the same position in the star-forming sequence as the central clump in this image, Sgr B1.

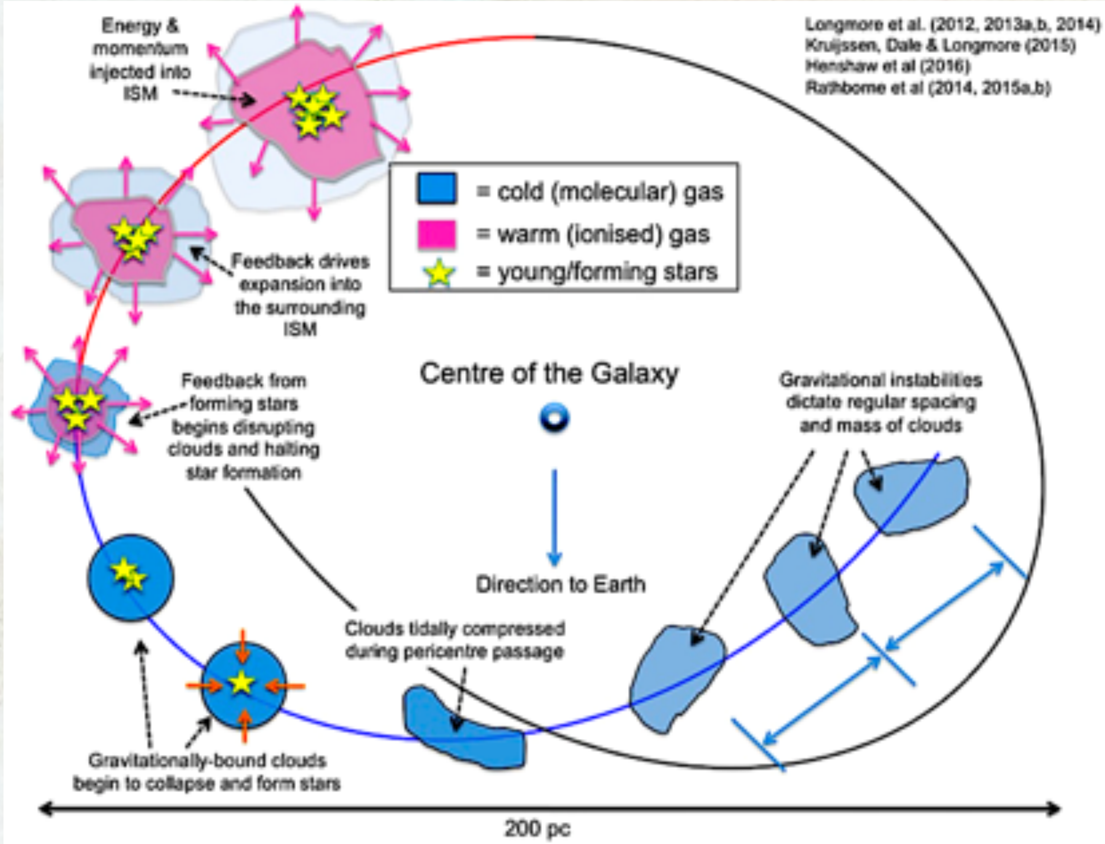


Fig. 12: How do astronomers go from the 2-D field shown in the image in Fig. 5 to a detailed 4-D reconstruction of the orbits of the original GMCs in orbit 100 kpc (326,000 lyr) around the Milky Way centre? At present the three equidistant blobs on the r. side of the above image correspond to the red H_2 gas clumps in the same location in the Fig. 5 image. How can astronomers predict the sequence of star formation and gas expulsion that is yet to come, as they have above? The short answer is high-resolution spectroscopy (to reveal the region's stars' ages and birthplaces) and computer models that calculate the paths of the clouds, which are moving ballistically. 'Ballistic' means motion through space under the influence of gravity. The not-too-technical answer is given fully in *Longmore et al 2016*.

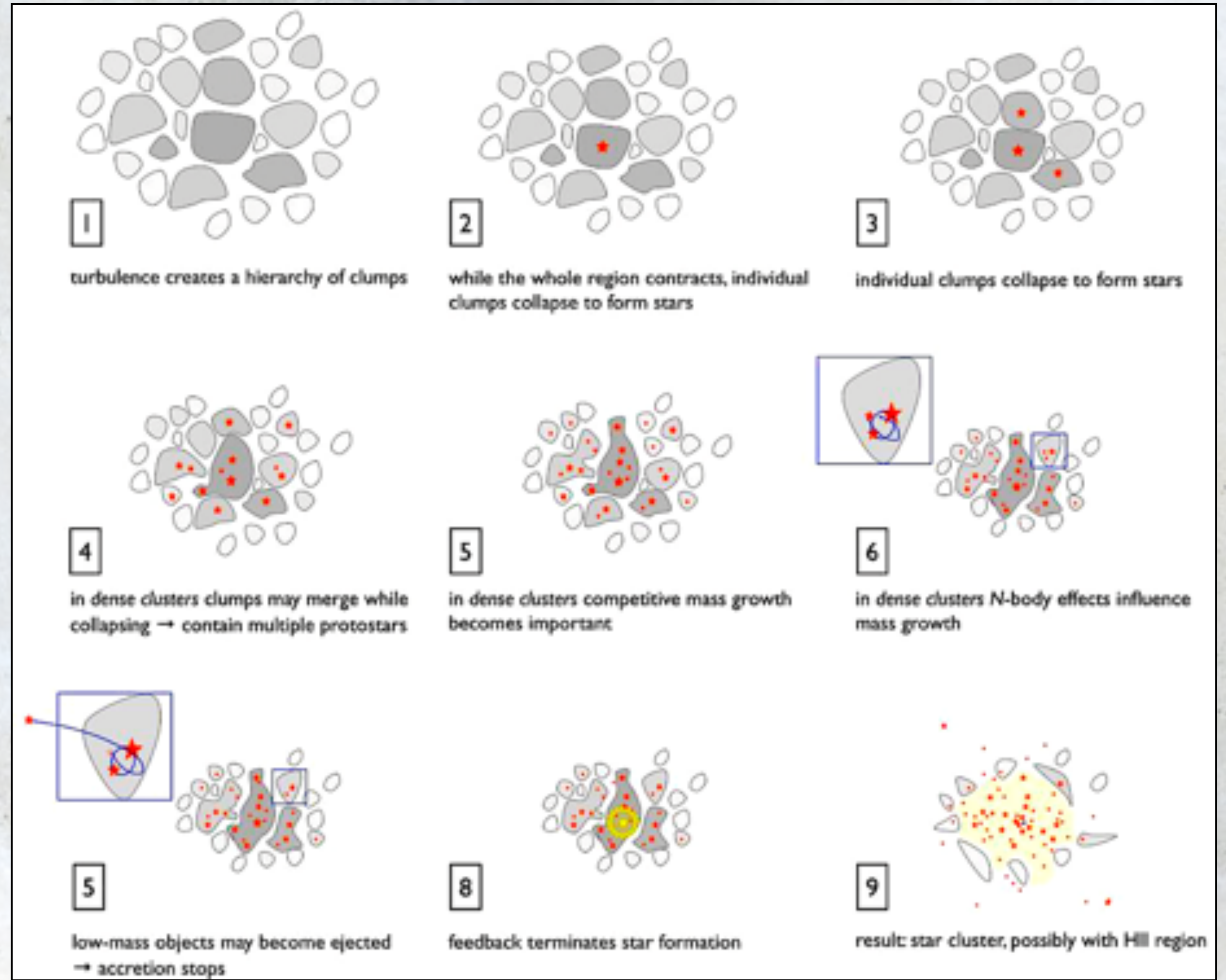


Fig. 13: Stars and clusters form by gravoturbulent fragmentation of interstellar gas clouds. Supersonic turbulence is ubiquitous in molecular gas. The shocks from interacting turbulence produe strong density fluctuations which inhibit star formation. Turbulence plays a dual role. On global scales it provides support; on smaller scales turbulence can promote local collapse. Magnetic fields generated by the same high-velocity turbulence bleed away the energy of the shock waves. Eventually gravity in the densest and most massive regions can initiate collapse into stars. Stellar birth is thus intimately linked to energy exchanges in the parental gas cloud, which in turn govern when and where protostars form and how they grow. Source: *Klessen 2011*.

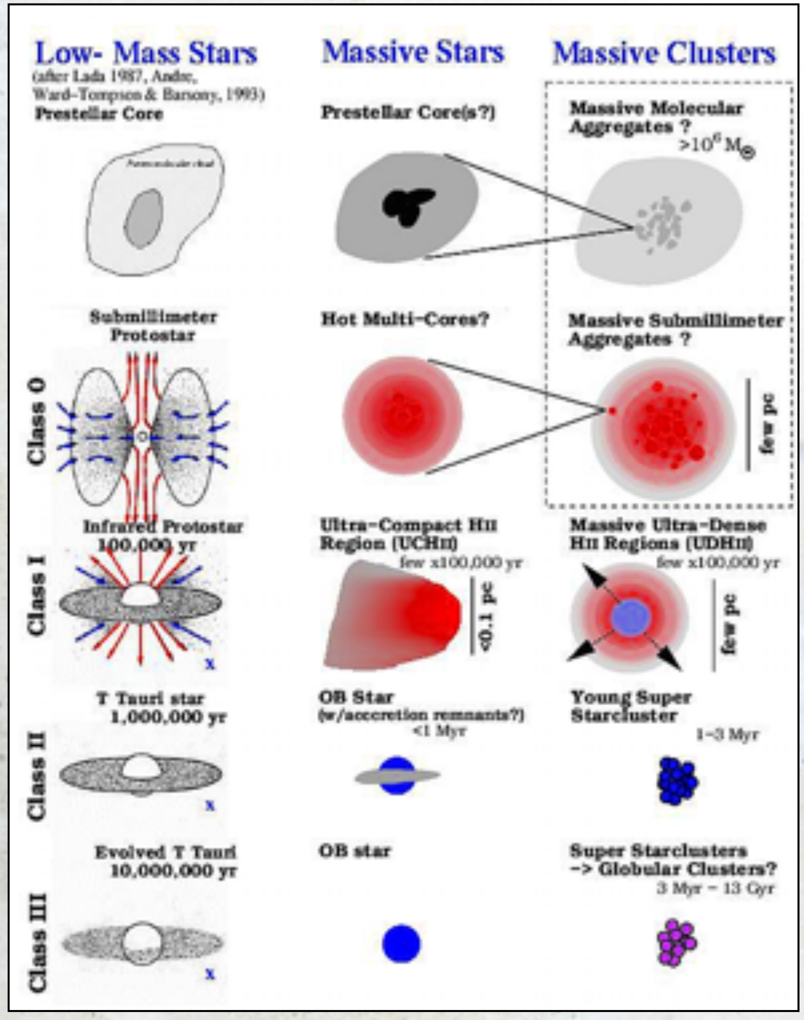


Fig. 14: In the cloud-collision star forming scenario, a dense gas cloud penetrates into a second similarly dense gas cloud. The initial contact front compresses and fragments into multi—layered turbulent shock fonts, which in turn dissipate into the filamentary structures, which in turn free-fall into "Pillar of Creation" type linear star forming clouds. Filamentary or "Pillar of Creation" gas blobs are the most common type of star-forming structure to result when two gas clouds collide. Inside those filaments, stars form in ragged linear lines. By the time the gas pillars evaporate from local UV radiation, the stars have lost their linearity and dissipate easily into the spiral disc.

At about 18K, carbonaceous rings on cosmic dust can intermediate between the electrons of two hydrogen atoms if they are close enough to each other that the electron orbitals cross. The outer atoms in the carbon molecules interact with the hydrogen molecules in such a way that the hydrogen atoms bond to each other, not the carbon. The result is H_2 or diatomic hydrogen. H_2 atoms on the surfaces of dust particles are the ONLY way dust can gather together until they reach densities high enough for the hydrogen atoms to fuse. Without interstellar dust, stars wouldn't exist and we wouldn't be reading this.

Atomic hydrogen clouds become molecular hydrogen clouds when the latter atoms gravitate into the centre, squeezing the hydrogen atoms out into a surrounding shell. In the case of W43 before it mass-segregated into the two clumps of today, its outer low-density envelope of atomic hydrogen is roughly 290 pc (940 ly) in diameter and its inner H_2 region was ~140 pc (456 ly) dia.. It contained enough gas to make more than 100,000 stars — although typically only about 3% to 5% of a molecular cloud's gas ever makes it into stars. The rest dissipates into the disc to give it another go many millions o years into the future.

Presently W43 is making a new star every 10 years. If we could see the thing we would have a Carina Nebula to wax lyrical over in northern skies.

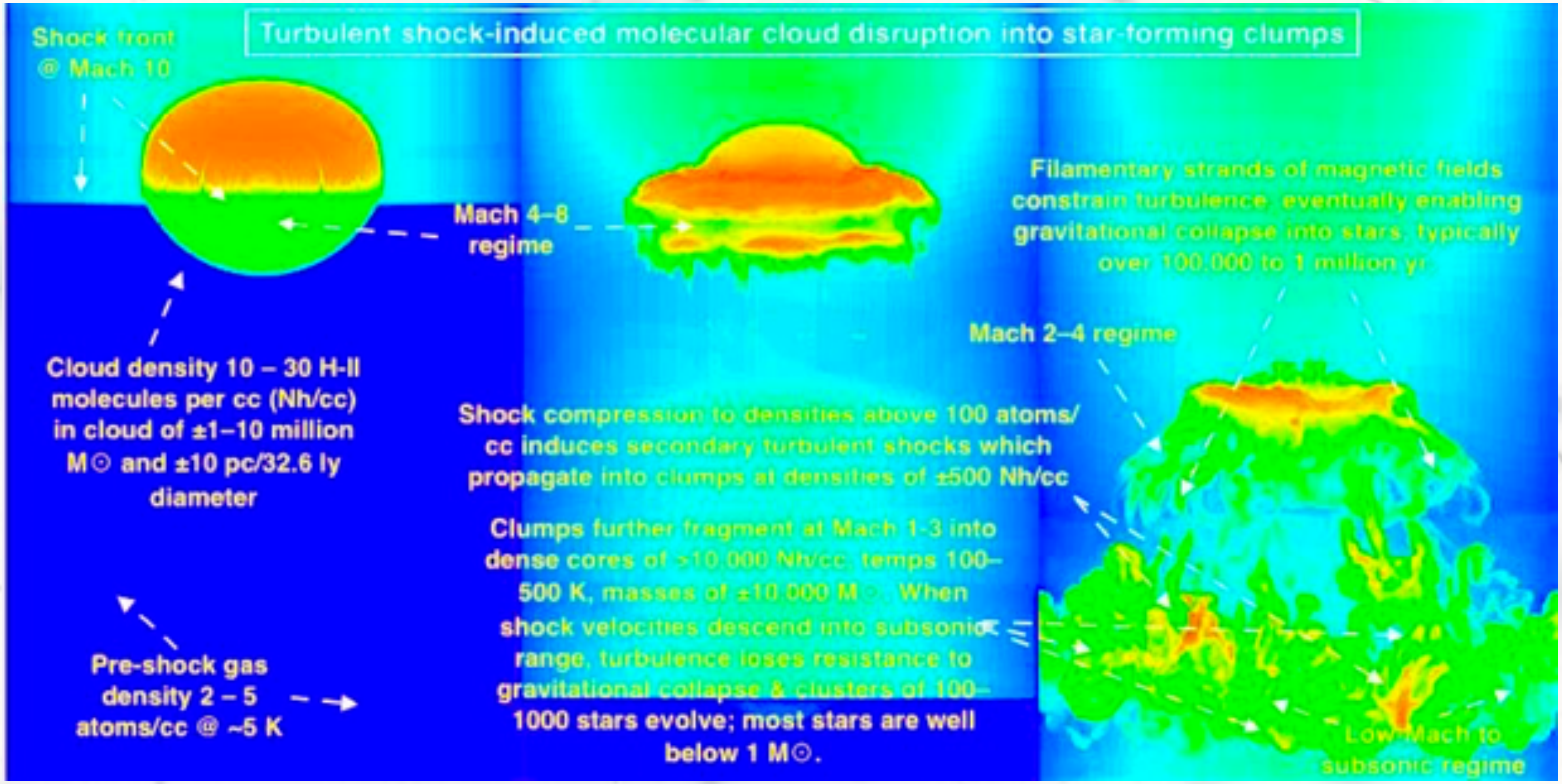


Fig. 15: This is an oversimplified schematic of W43, but it could be a poster child for cloud-cloud collisions in general. W43's low-density outer envelope of atomic hydrogen is a comma-shaped cloud roughly 290 pc (940 ly) in diameter with densities of 5–10 M H_1 cm^{-3}. The denser HII molecular region inside is ~140 pc (456 ly) dia. and has enough gas to make more than 50,000 suns. The average density of the comma-shaped cloud is ~10 N HII cm^{-3} at a temperature of ~30 K. The sound speed in such a gas is 0.3 km s^{-1} (680 mph), while average velocities in dense star forming regions are on the order of several to several tens of km s^{-1}. A velocity of 10 km s^{-1} would be Mach 33.3; and 30 km s^{-1} would be Mach 100. Source: Nguyen Luong A&A v.529 #A41 2011.

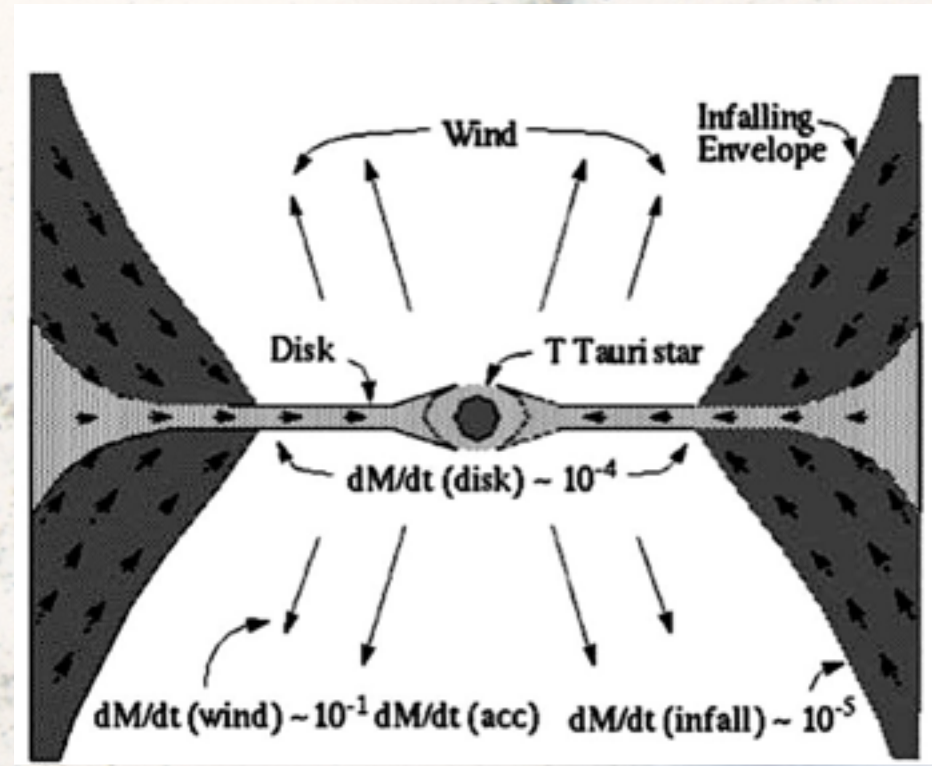


Fig. 16: Gas does not fall into a protostar from just any old direction. Protostars have high-energy magnetic fields whose field lines emerge out of their north poles, circle the star, and re-enter through their south poles (like the Earth and Sun's magnetic fields, called *poloidal* fields). The high-speed electrons that generate the magnetic fields originate in the solar wind of the star, and escape in vectors perpendicular to the field lines. Most of the wind is redirected toward and ejected from the polar regions. That leaves an energy deficit along the star's equator. The protostar was originally surrounded by a uniform envelope of gas, but the star's own magnetic field drove the gas away from its the polar regions, giving rise to a powerful inflow corridor along its rotational equator. Soon so much gas accretes onto the star that it cannot all reach the surface. Excess gas is redirected upward to the star's pole and ejected at very high velocity. So much thermal energy is generated that the polar regions generate large amounts of radiation in x-ray. Protostellar (aka T-Tauri) stars can be detected by their x-rays even if they are very dim in the visual and IR bands. Source: *Tsuboi et al 2014.*

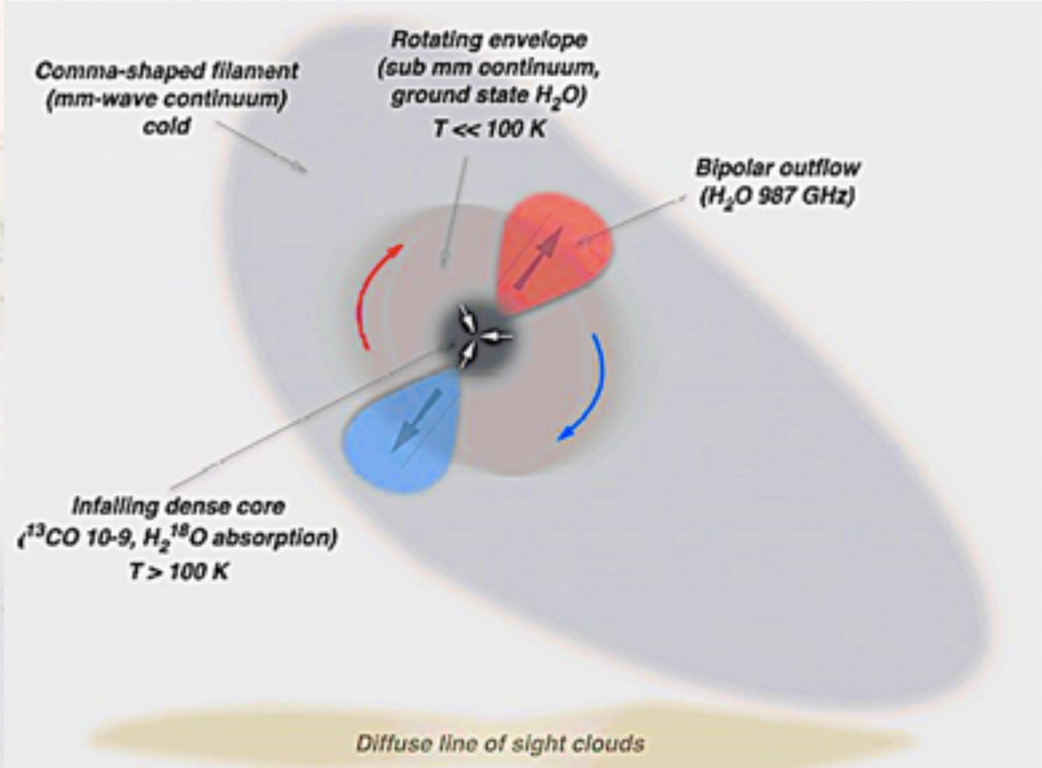


Fig. 17: This is an oversimplified schematic of W43, but it could be a poster child for cloud-cloud collisions in general. W43's low-density outer envelope of atomic hydrogen is a comma-shaped cloud roughly 290 pc (940 ly) in diameter with densities of 5–10 M_{HI} cm^{-3}. The denser H_2 molecular region inside is ~140 pc (456 ly) dia. and has enough gas to make more than 50,000 suns. The average density of the comma-shaped cloud is ~10 N_{H2} cm^{-3} at a temperature of ~30 K. The sound speed in such a gas is 0.3 km s^{-1} (680 mph), while average velocities in dense star forming regions are on the order of several to several tens of km s^{-1}. A velocity of 10 km s^{-1} would be Mach 33.3; and 30 km s^{-1} would be Mach 100. *Source: Nguyen Luong A&A v.529 #A41 2011*.

We don't know what the Scutum bar-arm confluence looks like from any other viewpoint than our 2-D in-plane tangential view. Between stellar crowding on one hand and extinctions of up to 10 magnitudes on the other, the Scutum Cloud can be fully portrayed only via multi-band observations from the 21 cm HI radio band up through mm band to far IR. What does it look like from above? The best-informed guesswork we have is *Robert Hurt's 2005 graphic* rendering of Robert Benjamin's Spitzer-based data in the GLIMPSE Point Source Catalog of ~30 million mid-infrared sources within 1° of the disc plane. GLIMPSE = Galactic Legacy Mid-Plane Survey Extraordinaire. This Franglaise mishmash is what happens when PR tries too hard for catchiness. *Source:* Adapted from Churchwell 2009 § 4.1. <*http://iopscience.iop.org/article/10.1086/597811/pdf*

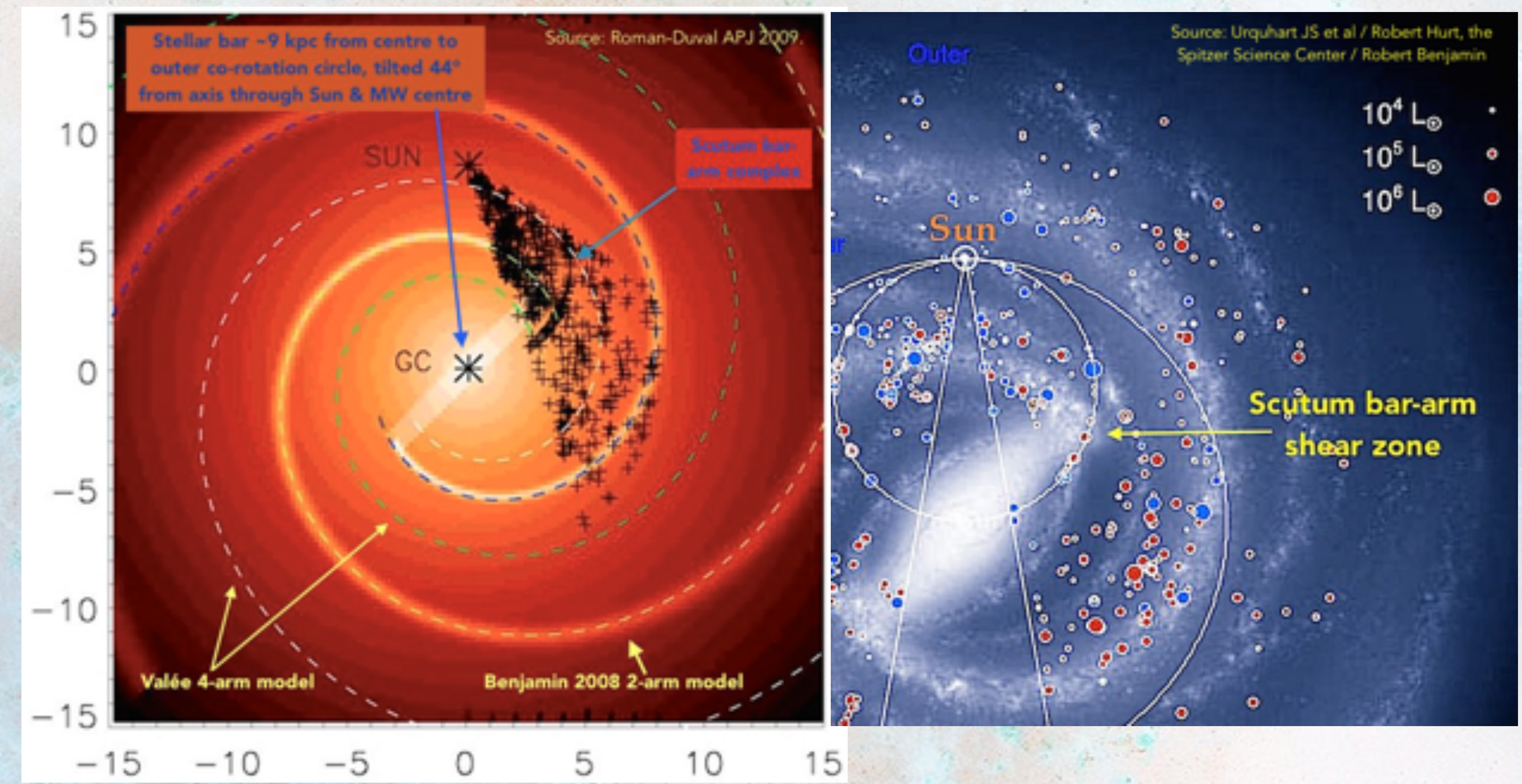
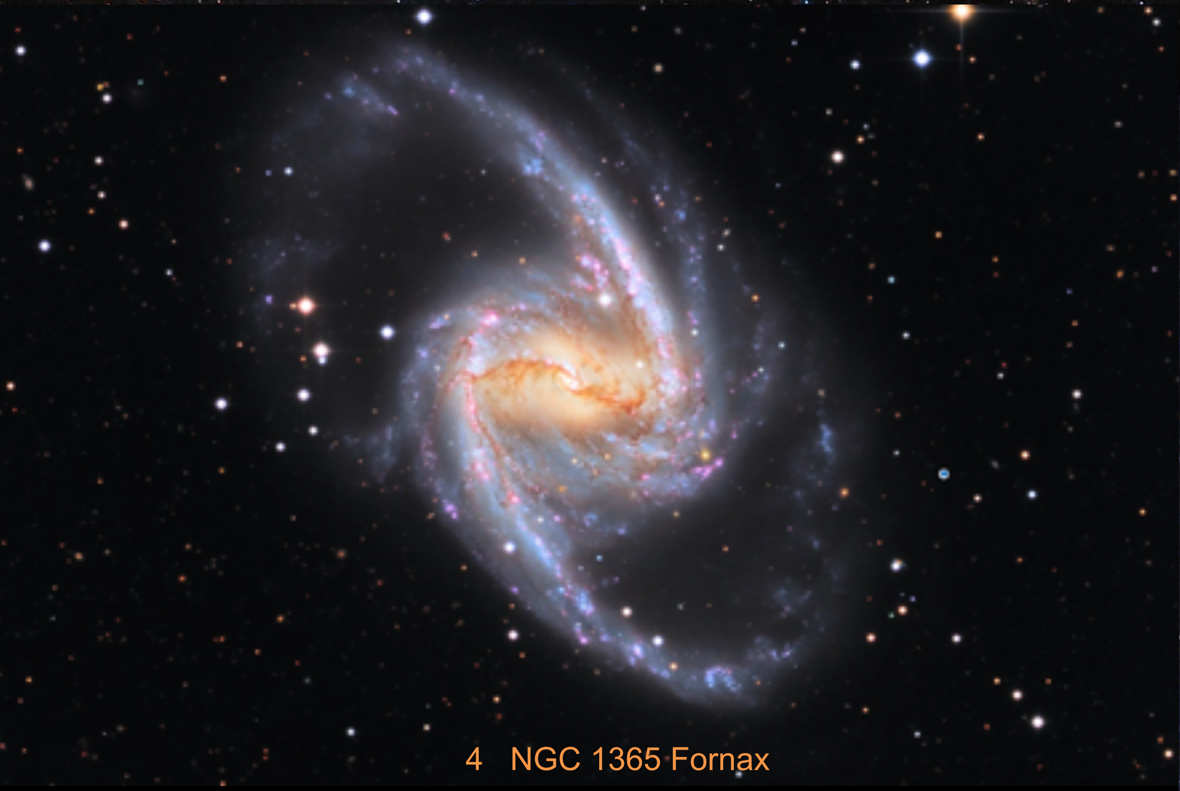


Fig. 18: Source crowding between Sun and Scutum bar-arm shear zone. *Left:* crosses mark >10^6 $M_\odot$ molecular clouds from ^{13}CO Galactic surface brightness Galactic Ring Survey (*Roman-Duval 2009*) based on 829 molecular clouds identified by Rathborne et al. 2009, *Right:* Galactic distribution of massive young stars (red circles) and compact and ultra-compact H II regions (blue circles) 10^4–10^6 $L_\odot$ (*Urquhart 2006*). *X-* and *y-*axes demarked in kpc.

The winds of change are blowing over Aquila – III

1 NGC 6744 Pavo

2 NGC 1073 Cetus



4 NGC 1365 Fornax

3 NGC 4394 Coma Berenices

How do galaxies get their bars?

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, and. 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 trischophrenic: their dense stars rotate in one manner; their light, loose gas clouds rotate in another; and their heavier, loose 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.

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)

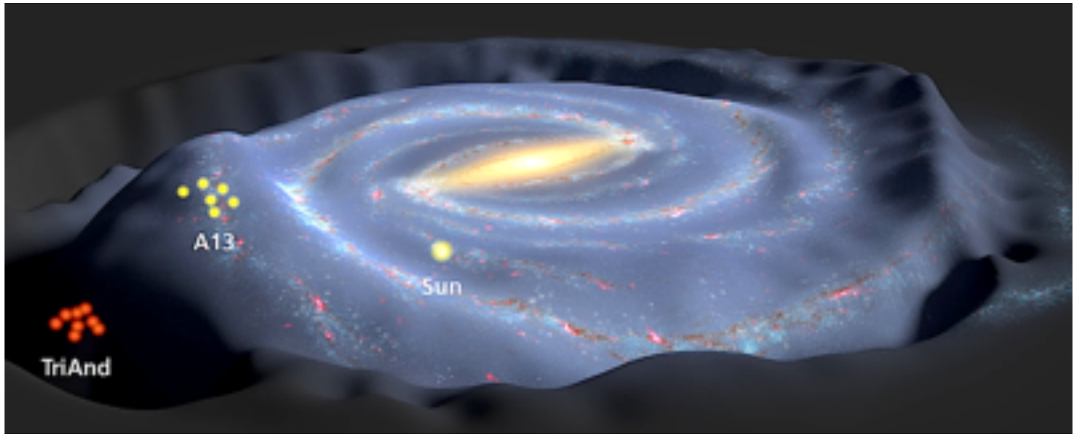


Fig. 19: Earlier this year *Bergemann et al 2018* studied two groups of stars in the outer Perseus Arm very far apart from each other yet exhibited identical spectra. Both star sets exhibited nearly identical metallicity, age, size, and velocity. There was a high probability that they originated in the 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.

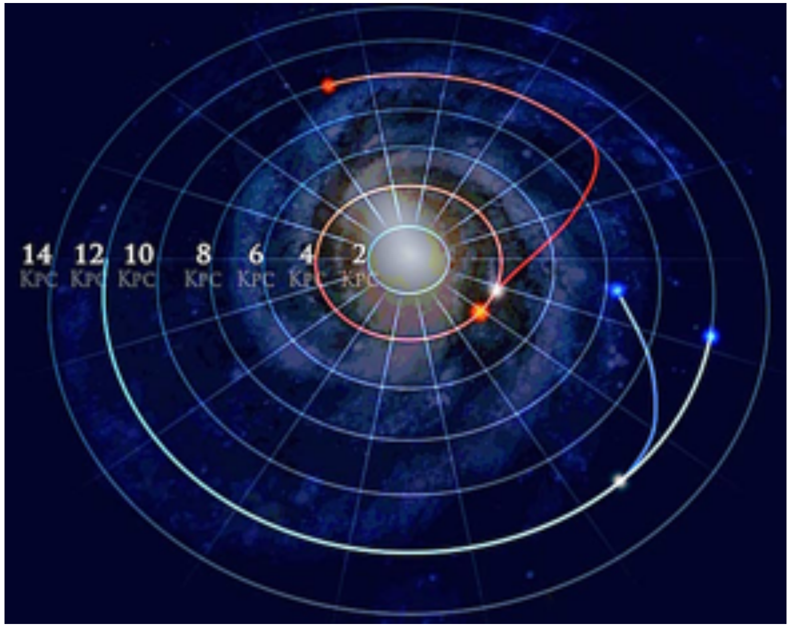
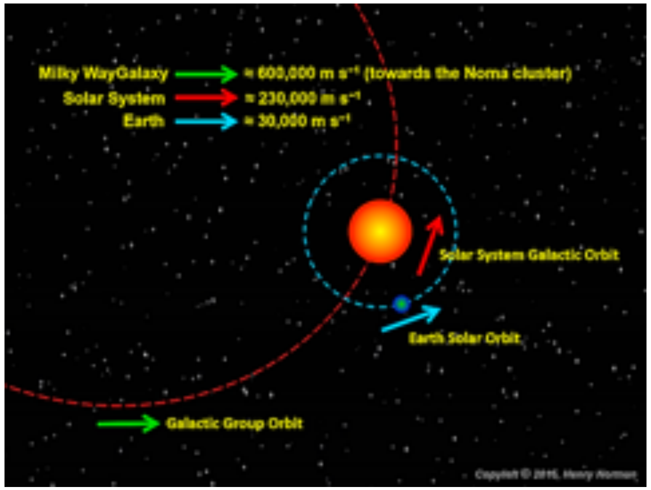


Fig. 20: A wandering star can move a long way in several billion years. *Michael Hayden et al* 2015 found that up to 30% of chemically mappable red giants originated in locations far from their current homes. Some of their migrations originated when massive binary stars ejected a smaller interloper (the 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. 21: 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.



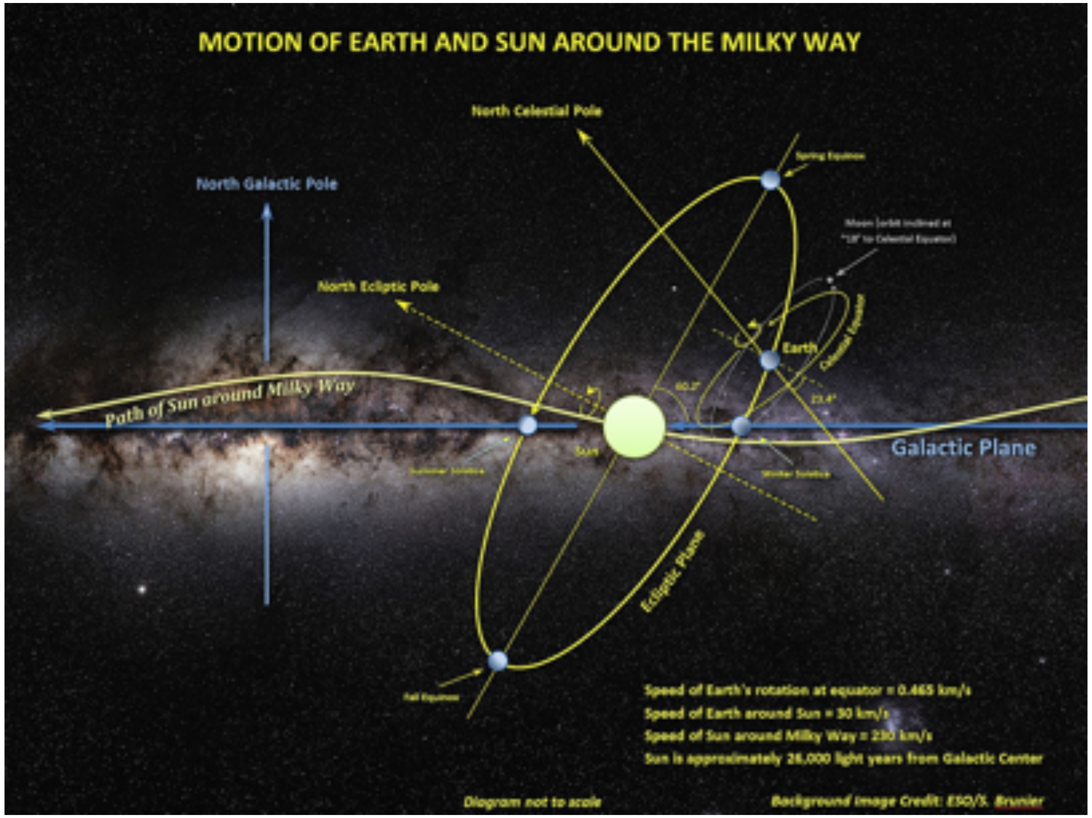


Fig. 22: A star has three ranges of motion (epicycles) as it rotates around a galaxy: up and down, side-to-side, and fore and aft along the vector its forward path. The Sun's main deviation from a true circle around the disc is up and down. That motion was likely imparted by the gravitational fields 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.

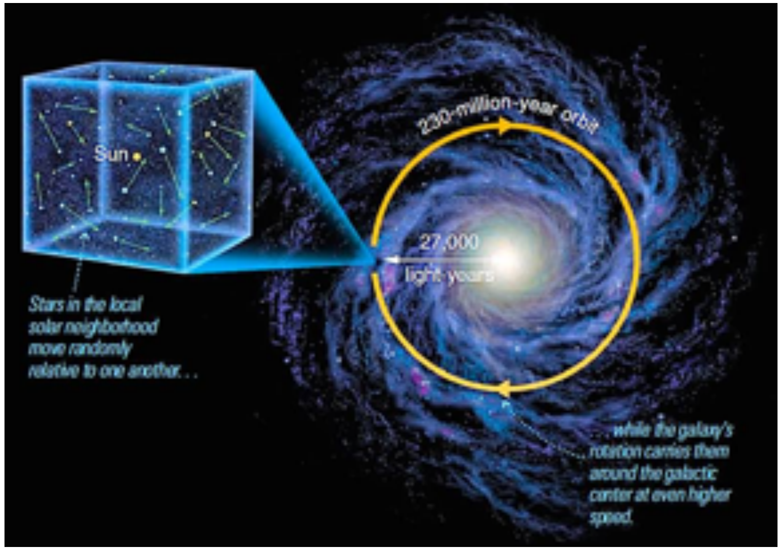


Fig. 23: Using the bee-swarm analogy, a 10 pc parcel of stars centred on the Sun rotates around the galaxy in a near-circle, but the stars within each parcel have their own significant peculiar motion in relation to the others. The most significant perturbation on a parcel will be its transit through a spiral wave. Low-mass clusters are scattered during an arm crossing.

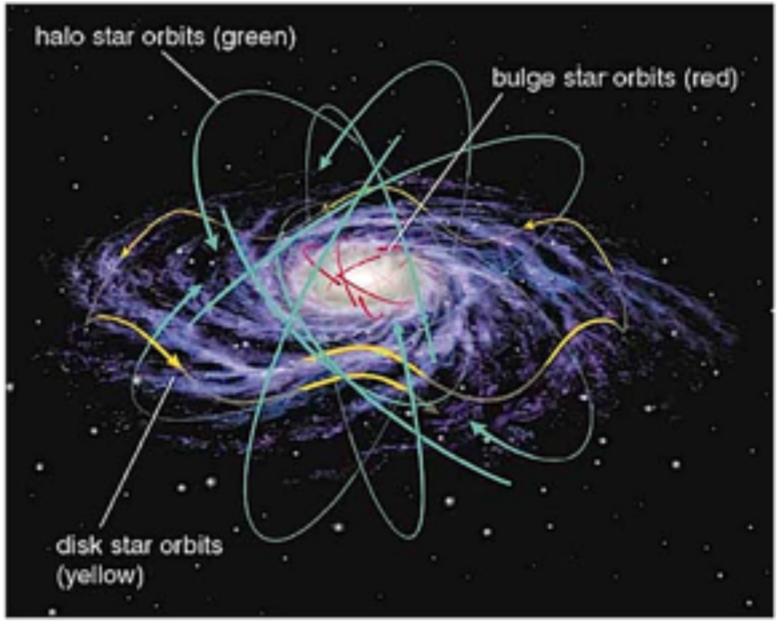


Fig. 24: Disc galaxies have three major families of stellar orbits around the centre. Bulge stars rotate in quasi-ellipses that are constantly rearranged by the stars swirling around them. Globular clusters and elliptical galaxies share this life of orbital inconstancy. Disc stars are described in more detail in the text. Halo star orbits are large, slow, and near-circular.

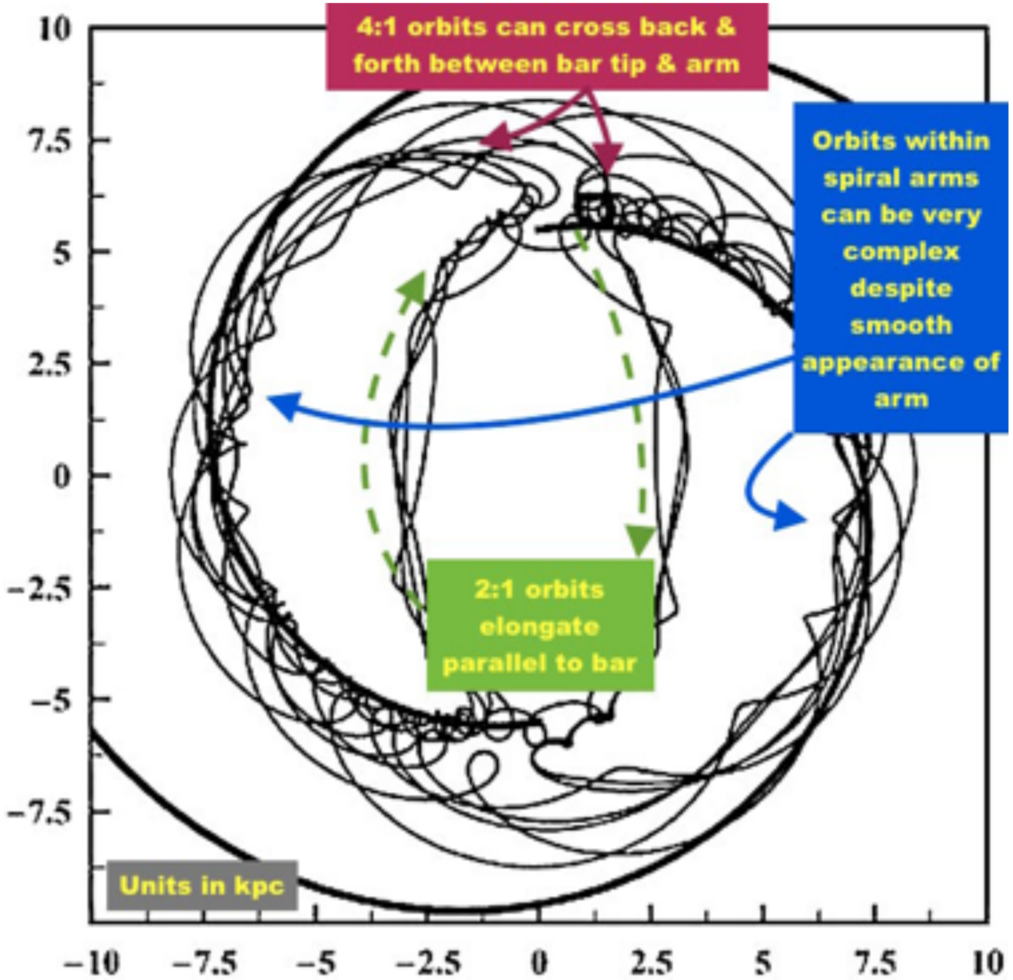
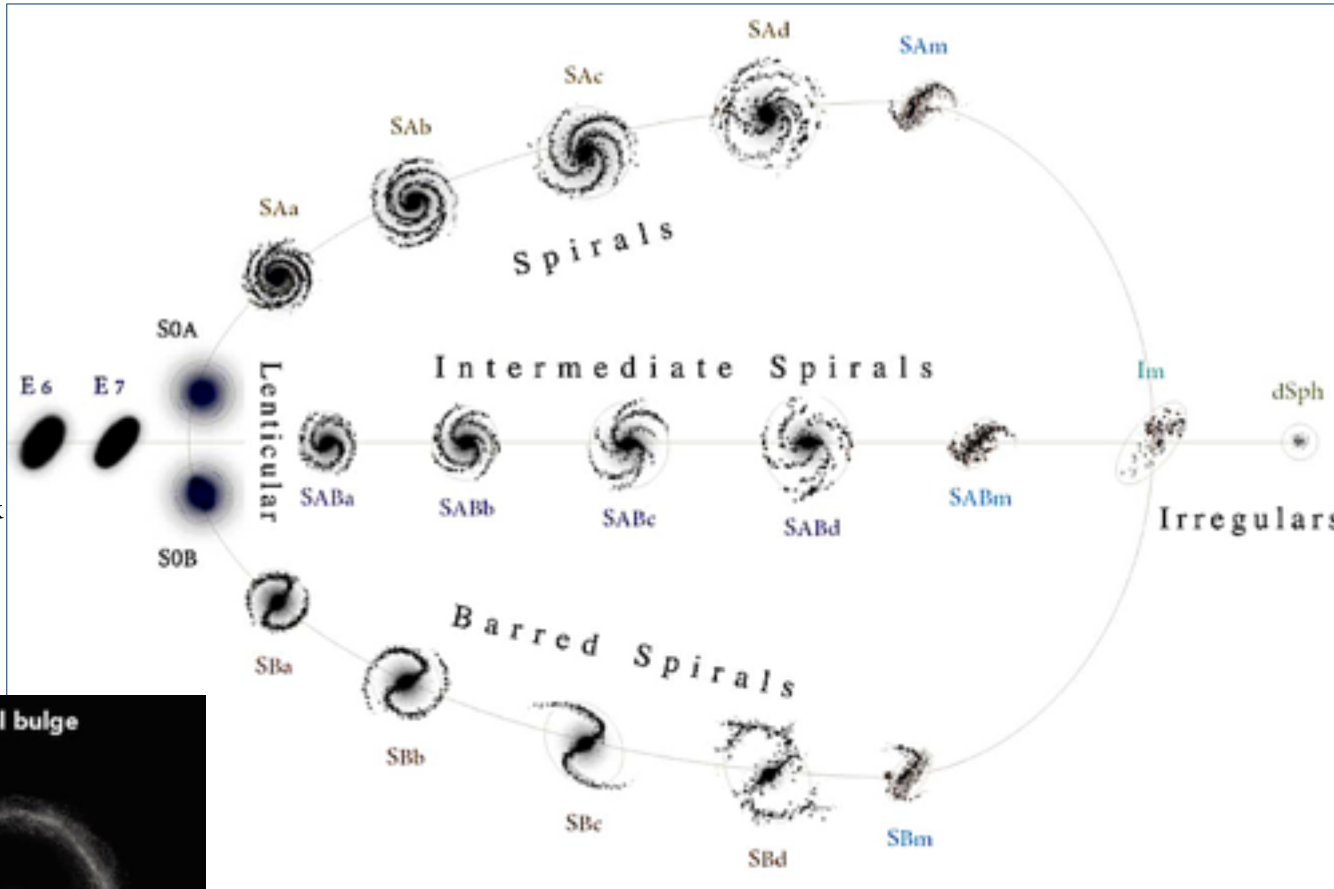


Fig. 25: Variations of peculiar orbits in a sample of six stars rotating around a barred galaxy. The lines here show star paths along their guiding centres, not the rotation of the entire ensemble around the galactic centre. This orbital plot traces a central bar extending into a spiral arm in the early 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.

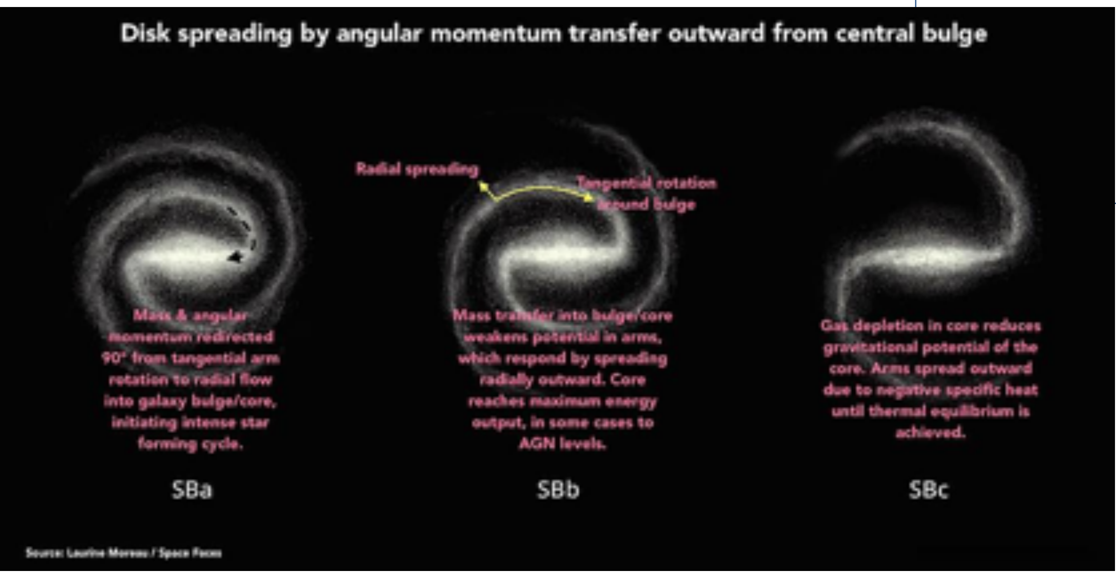
The original 1929 Hubble system provided the first ordering of galaxies that represented more than mere changes in optical appearance. In 1959 Gerárd de Vaucouleurs examined the central regions of galaxies and classified galaxies into strong bars, small or weak bars, and non-barred galaxies. He denoted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

How do galaxies get bars?

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 "crash diet overreach"

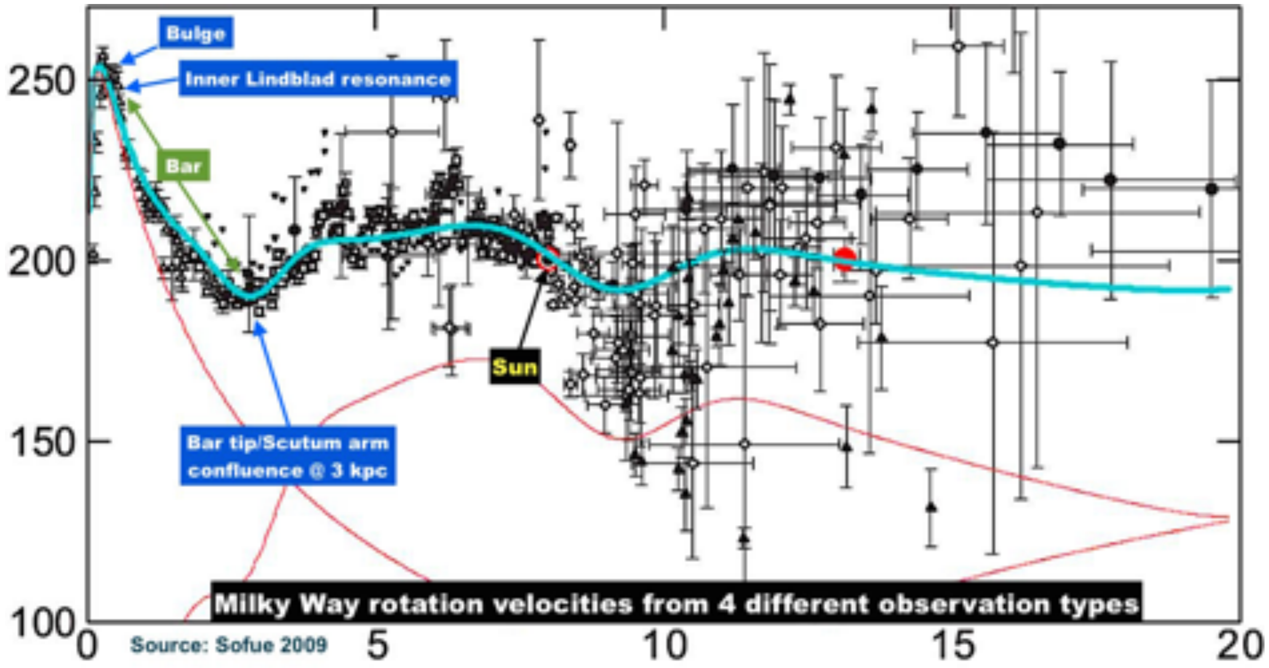
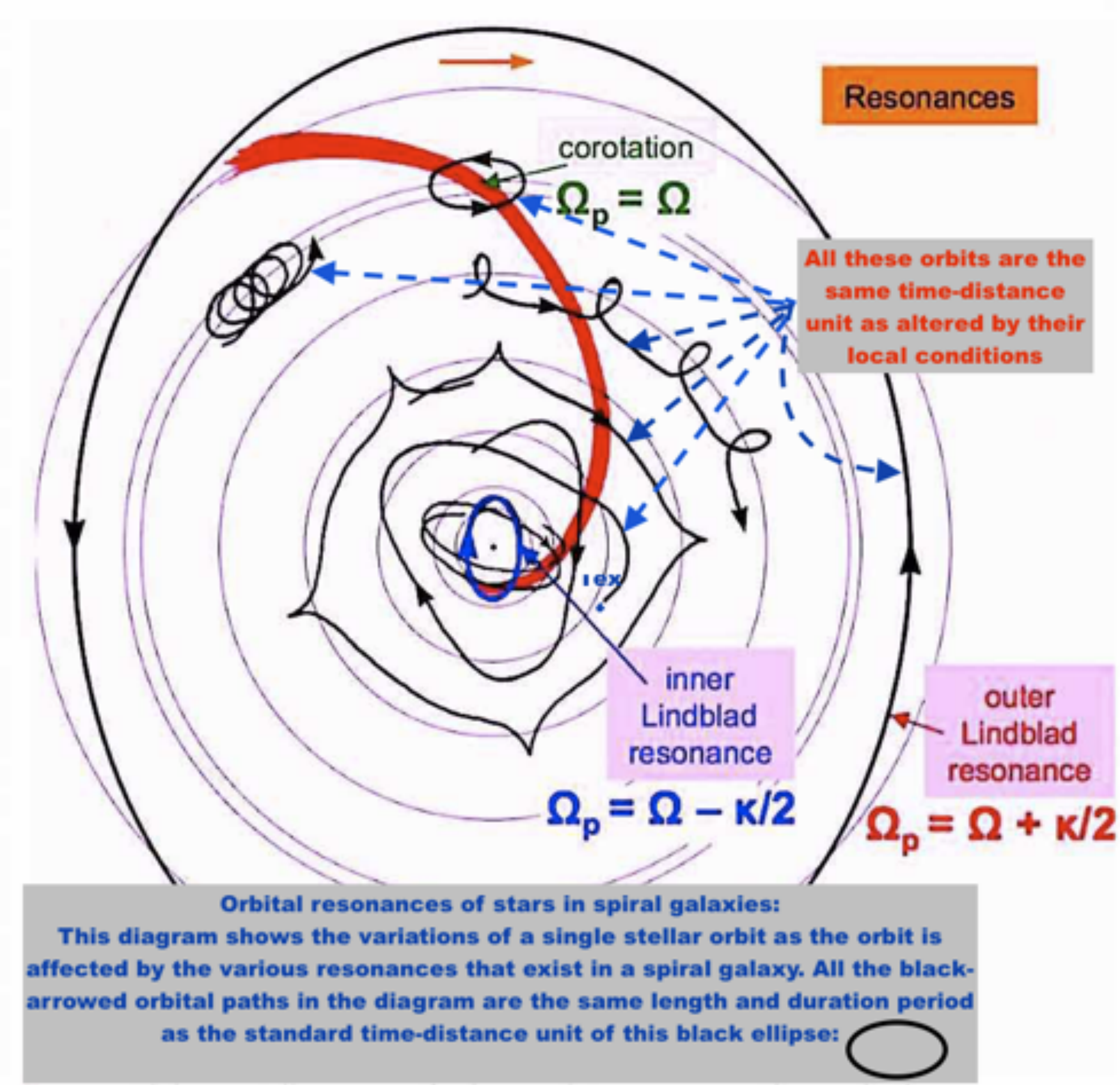


Fig. 26: Rotational velocities along Milky Way disc plane as presented in *Sofue 2009*. The rapid drop in rotational velocity between the Inner Lindblad Resonance and 3.5 kpc bar-arm confluence suggests a maturing bar whose rotational pattern speed is not yet uniform along its length. The large error bars beyond the Sun and co-rotation torus reflect uncertainties induced by source crowding, differential extinction, and small number statistics.

Fig. 27: 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. *Source: Kormendy 2013*. For more details about *Bertil Lindblad* see also 1, 2, 3, 4.



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 on p.3. In the CR stars and the spiral wave advance forward at close to the same speed (e.g., ±220 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 characterise 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.

What exactly is the bar's job description? What is it for?

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, a process called virialisation. Bars move gas inward towards their host's bulge. 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, hence so is their fuel. Where's 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.

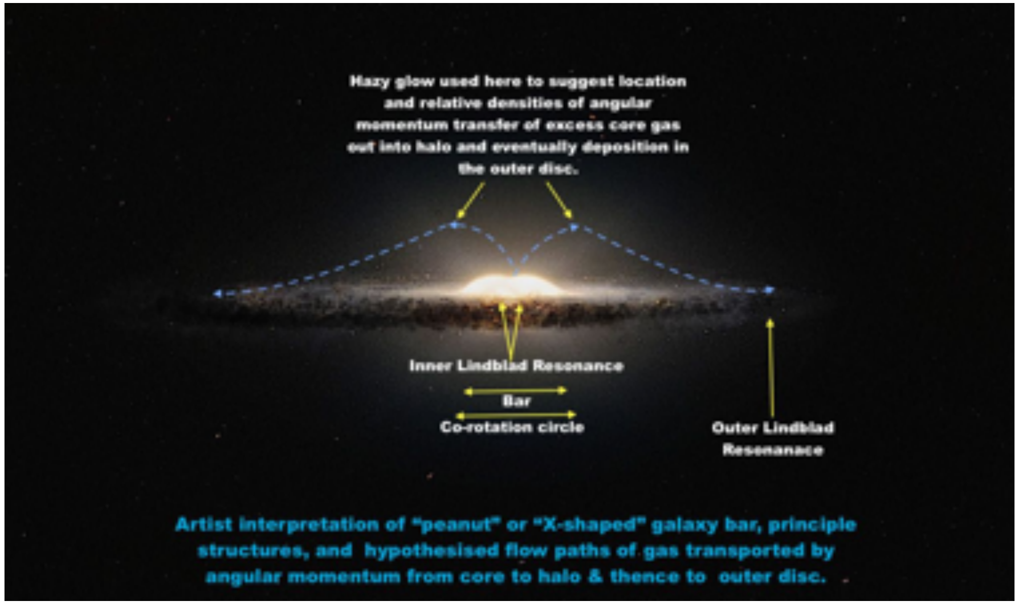


Fig. 28: Bars redirect large amounts of gas into the bulge to fuel star formation. Over time, more gas is delivered to the bulge than it consumes. Angular momentum transfer shifts some of the excess gas into the halo, where it then flows outward. In this sense, galaxies are large-scale heat engines. 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 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.

How stars rotate in barred spiral galaxies

Galactic bars are not as serene as their vapourous visual look 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. If all this is a nightmare of mixed metaphors, welcome to the mishmash world of barred galaxies.

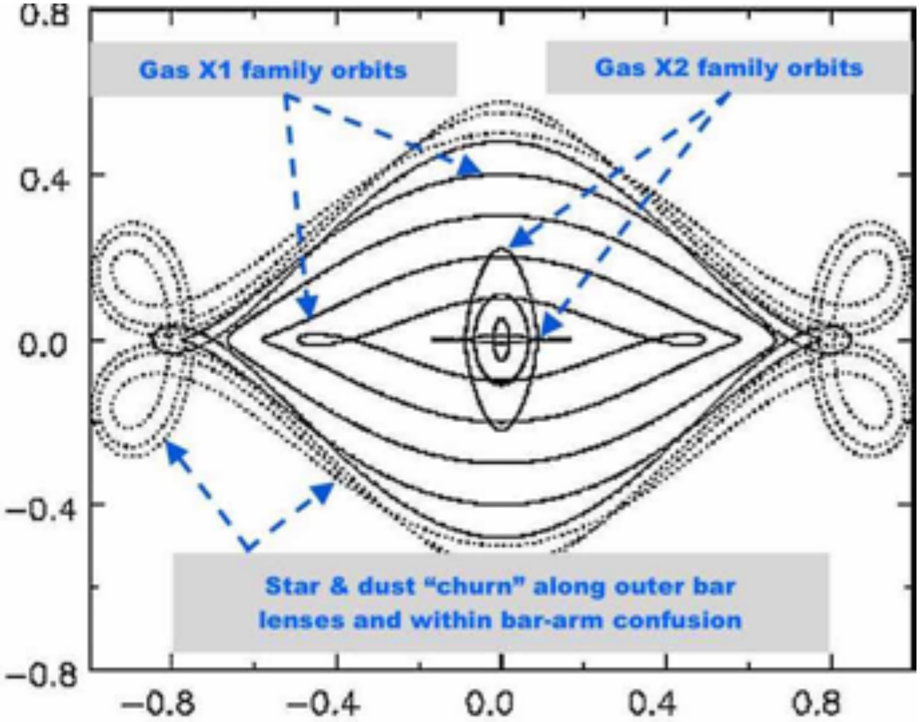


Fig. 29: The torque and shear forces that disrupt the spiral arm's gas clouds are so strong that they decouple gas from its clouds and stream the gas into a featureless surface. Two orbital families result: those which shuttle back and forth from spiral arm to spiral arm, named x_1, and a perpendicular family, x_2, that eventually will evolve into a pseudobulge. *Source:* Bournaud & Combes 2002.

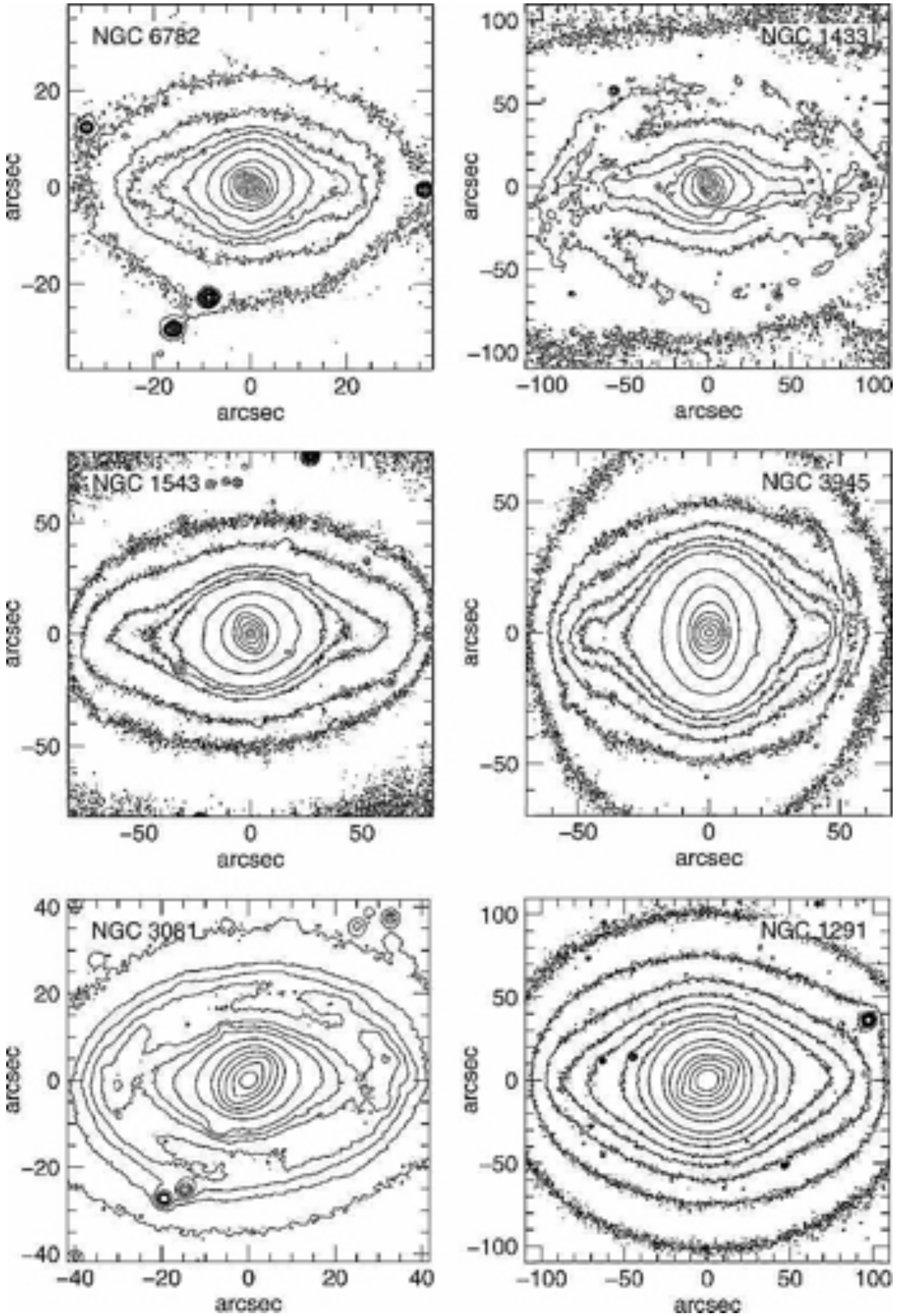


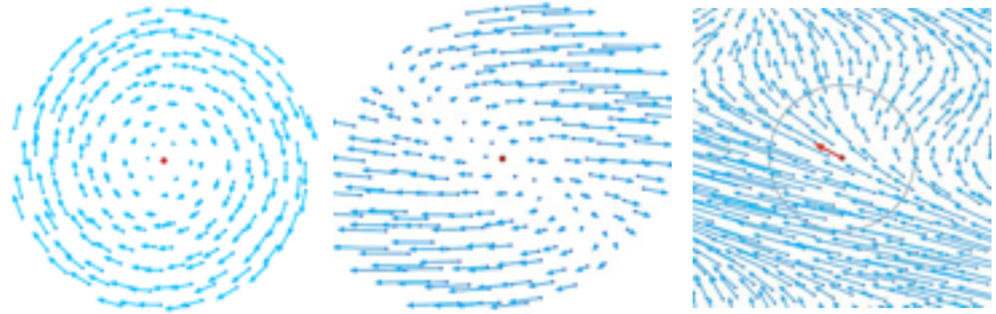
Fig. 30: When galaxy bulges accumulate *bulge-to-bar mass ratios* of ~62%, shear forces induced by the bar's orbiting families (above) induce the formation of a secondary bar inside the ILR of the bulge. The new inner bar has the same features as a spiral arm bar, e.g., a surface brightness profile that 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.

Why would an enormously massive spiral arm suddenly turn a 90° corner?

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 circular galaxy spontaneously form a horizontal bar that ends up disrupting the whole thing?

Inside a spiral, the surrounding medium behaves like a gas mixed with many solid particles. 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". (Please don't follow this example when naming your next child.) 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 of many small masses (star clusters and galaxies) have five *Lagrange points*.



Rotational vectors flow around a central force unless disturbed by an

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

Shear tensors are a common flow made of many individual perturbation vectors responding continuously

Fig. 30: At an inner resonance, a star's orbital speed is increased, moving the star outwards, and decreased for an outer resonance causing inward movement.

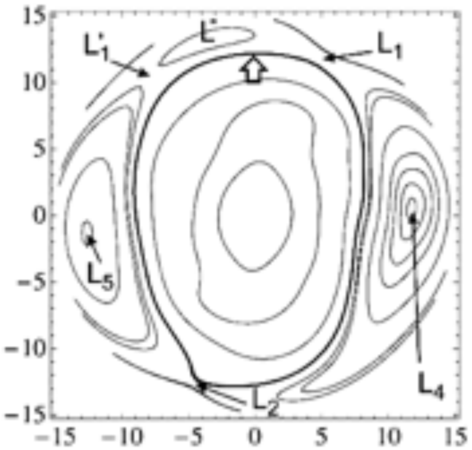


Fig. 31: Lagrange points in NGC 1300 are like eddies of a paddle that stirs its rotation. *Source: Athanassoula 2012*.

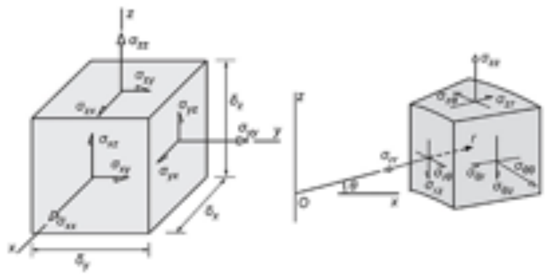


Fig. 32: On the scale of a galaxy, arms and bars behave like a fluid, not a gas. The myriad particles or stars and gas clouds each has its vector wothin the galaxy's gravitational well. The combined flow of these countless individual vectors is described by a branch of mathematics called tensors. As 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.

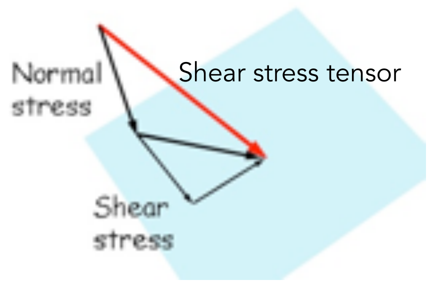


Fig 33: A shear tensor is a way of calculating the actual direction of multiple interacting forces. Calculating the cumulative effect of trillions of particles moving in spacetime requires enormous computing power.

Not much in the universe is truly local. The bar-arm confluence which so beguiles our splendid Milky Way arching overhead is a walk-on part in an allegory more complex than the world's literary epics. 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.

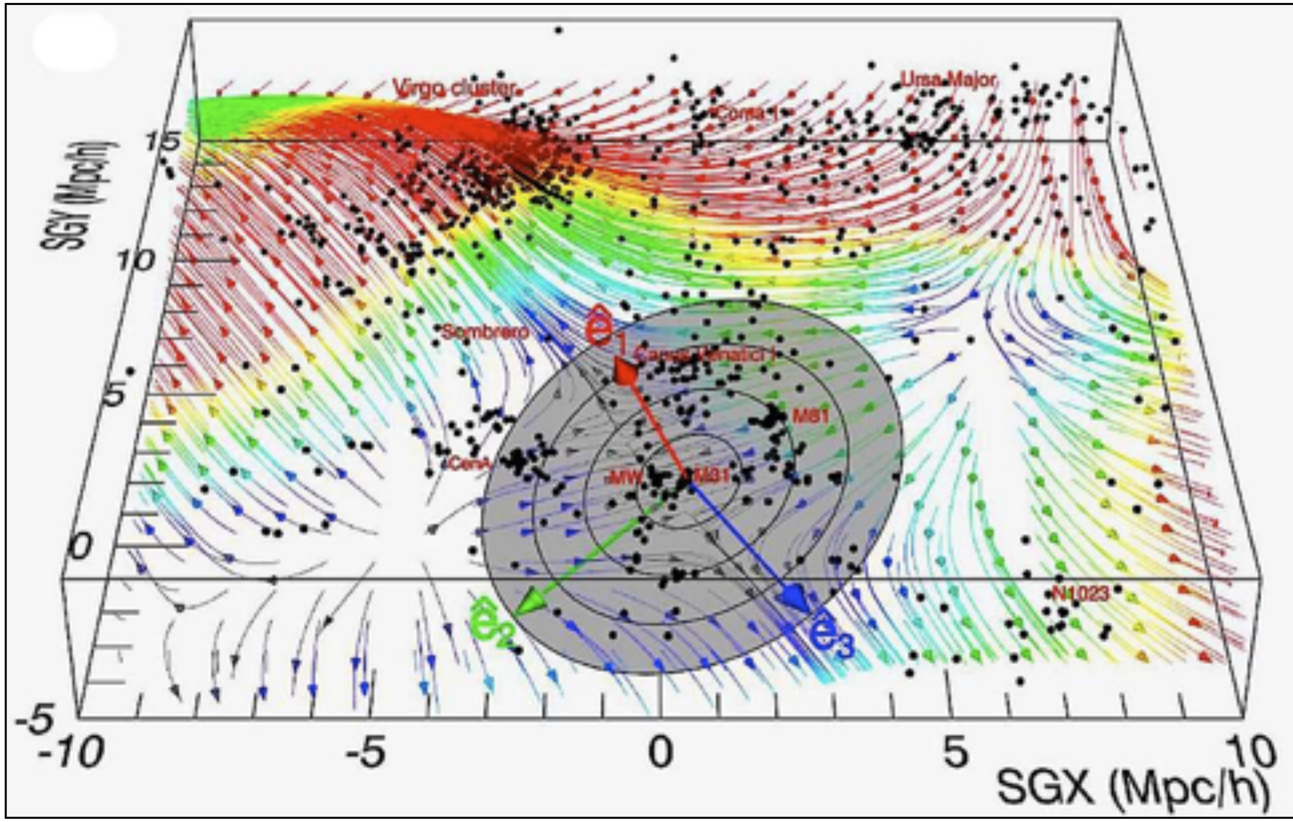


Fig. 34: The bar-arm confluence spanning the sky from Aquila to Norma is a modest example of universal physical processes that give shape to the entire Cosmic Web. In this image by Daniel Pomarède, the Local Group, M81 Group, Centaurus Cluster, and Sculptor Group are all infalling toward a shear stress 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.

What does angular momentum transfer do?

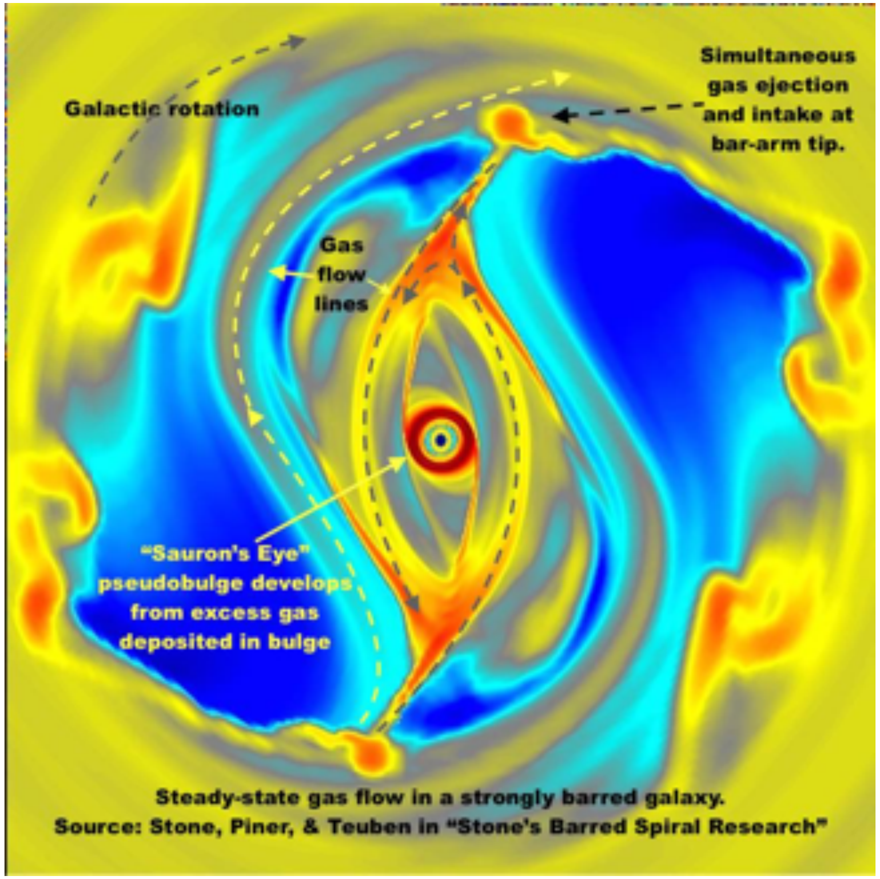


Fig. 35: Still frame from six-second 1.3 MB movie simulation of gas flow in a late-stage barred spiral galaxy by Princeton's Jim Stone. Titled *Gas flow in Barred Galaxies* (*view & download the sim here.*), the sim portrays gas behaviour only; no stars are involved. The sim reproduces the more obvious 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.

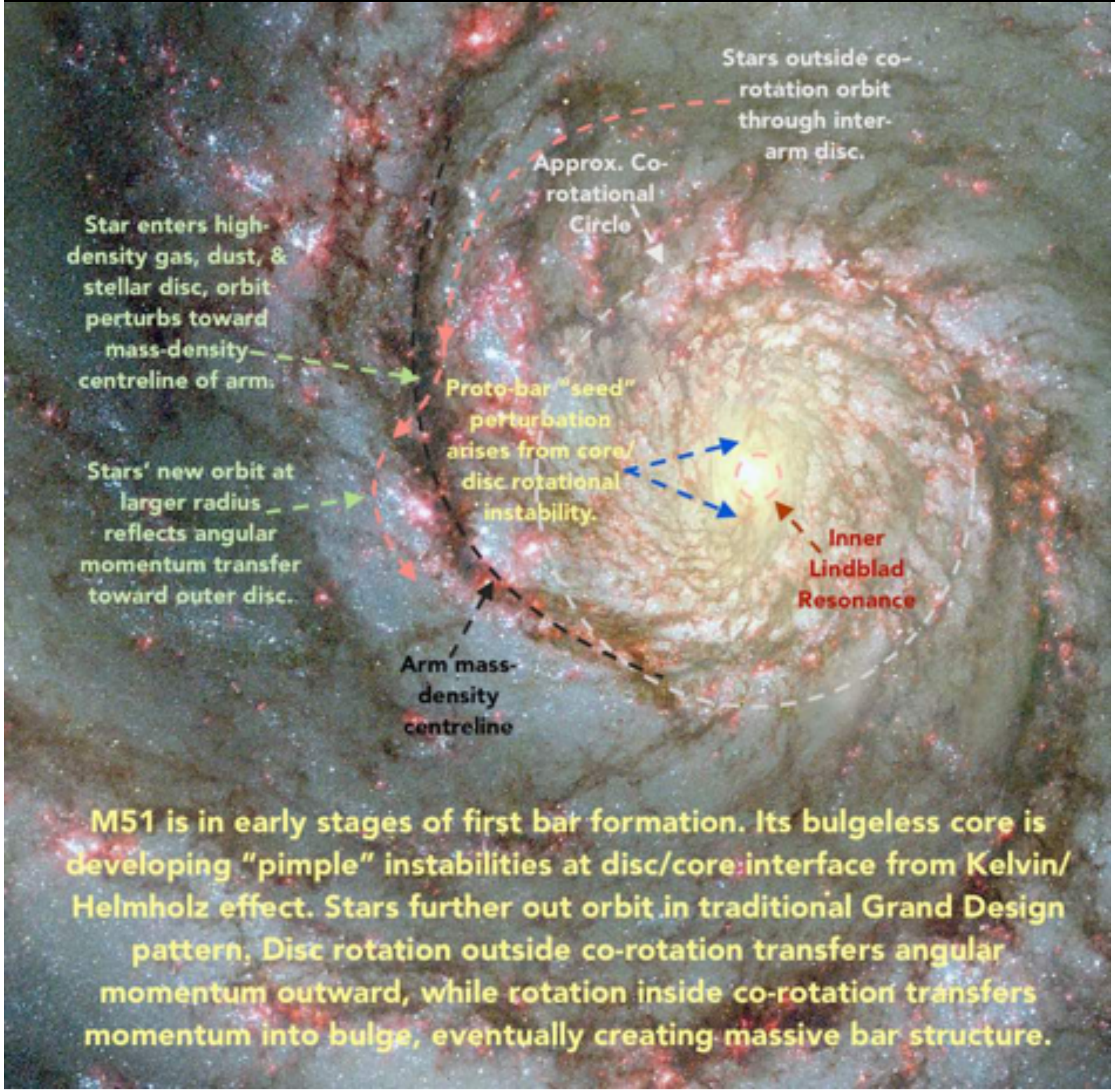
The virial theorem tells us that 2KE + PE = 0, where KE means kinetic energy and PE is potential energy. The number 2 is in this picture because it takes as much energy to bring a system back to equilibrium as it did to make a mess of it in the first place. Put another way, it takes as much energy to 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 start?



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. 8, p.10)
(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.

Fig. 36: 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.

Fig. 37: 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.

How angular momentum works in the Milky Way

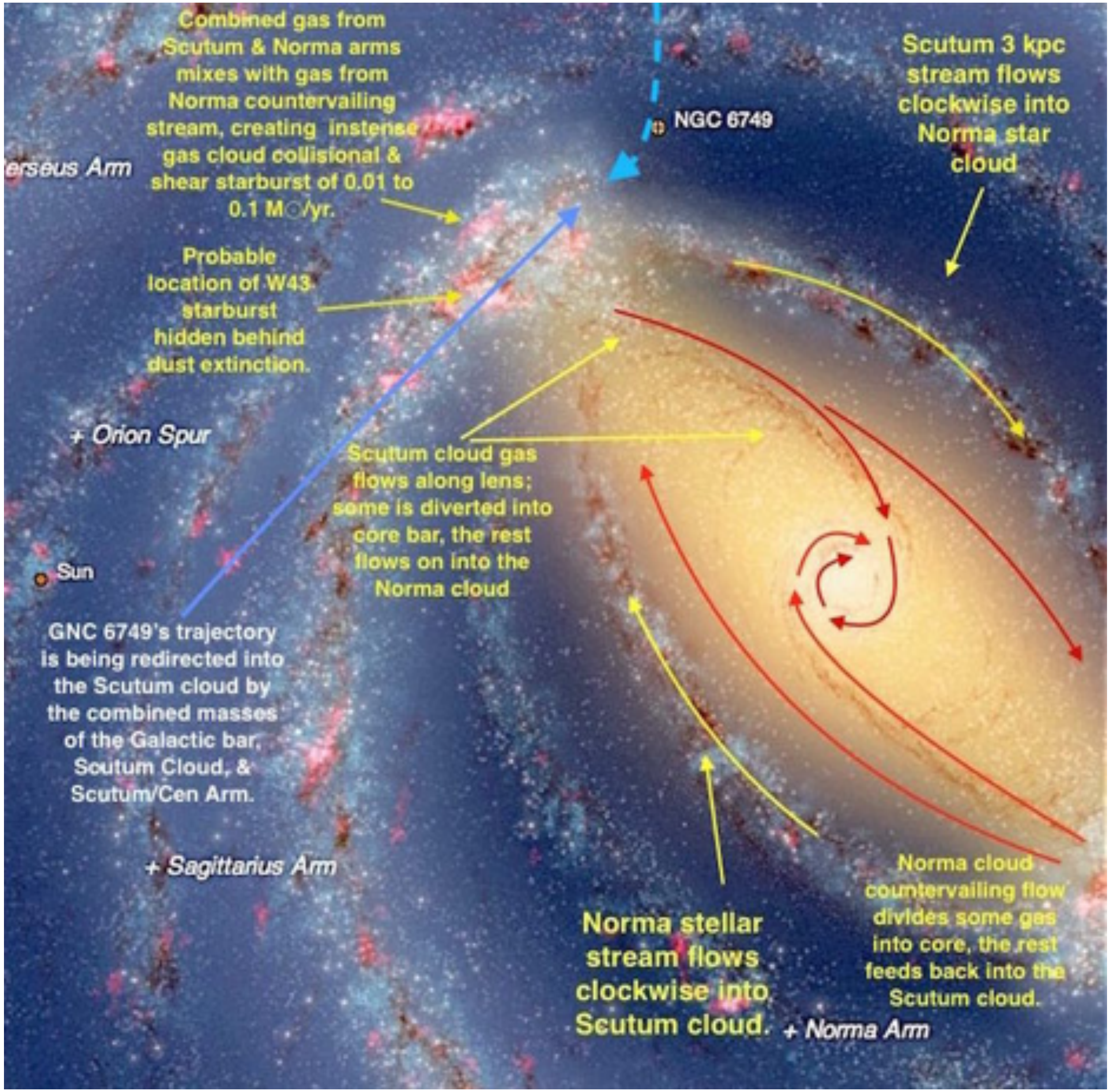


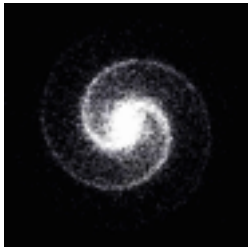
Fig. 38: The beclotted character of stellar and gas populations in spiral arms changes dramatically when they enter the chaotic bar-arm confluence at the outer tip of the bar. Star formation there is intense — e.g., the W43 cloud complex in Aquila. In many galaxies the spiral arm stars are re-orbited 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.

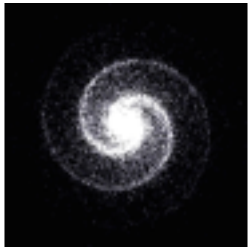
DIY galaxy sims

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.

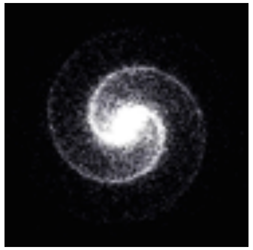
Sims have moved out of the mainframe world and onto your desktop. Any computer-literate amateur with a reasonable knowledge of coding and a basic grasp of astronomical physics can make their own simulations for self-study or to show friends. There are numerous pre-made algorithms and source code libraries 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:



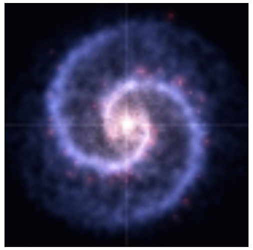
Rotation producing winding problem.



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. 39: In a classical Grand Design 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 has been transferred there from the highly active core region, igniting a fierce star forming episode.

Case study: NGC 1300 Eridanus

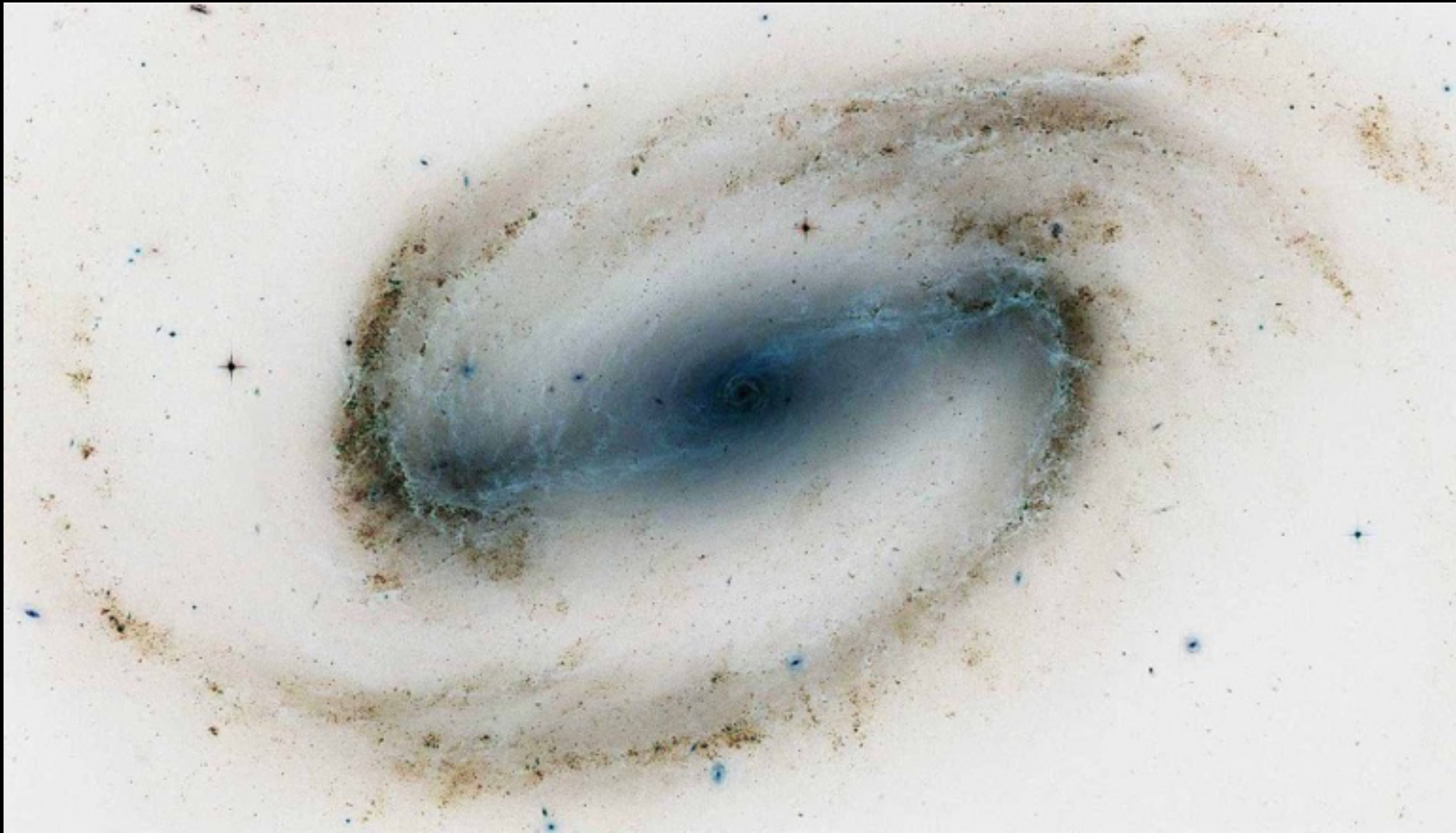


Fig. 40: NGC 1300 Eridanus is at a more advanced stage of bar development than the Milky Way's bar in its present stage. The colour scale of the image has been inverted to highlight the filamentary character of dust streams in the bar compared with the diffuse gas in bluish tones. Note how the dust filaments 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.

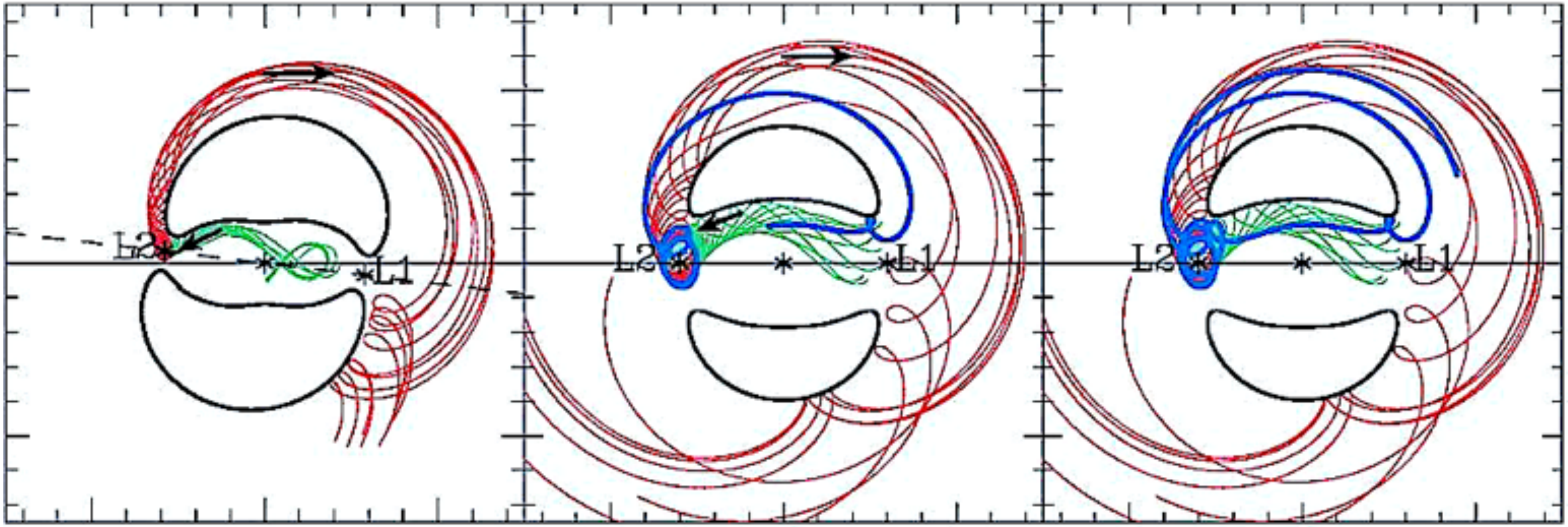


Fig. 41: Most accounts of galactic bars lavish attention on the bars. They are indeed beautiful, complex, and intricate, in the rather stiffly formal way that Bolshoi ballets were precisely structured. However, glance away from the pretty *pas de deux* in centre stage and take in the large view of the 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.

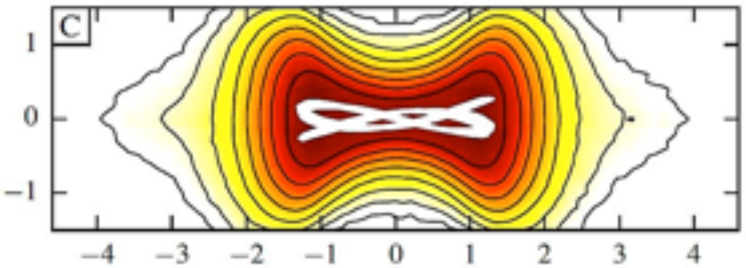
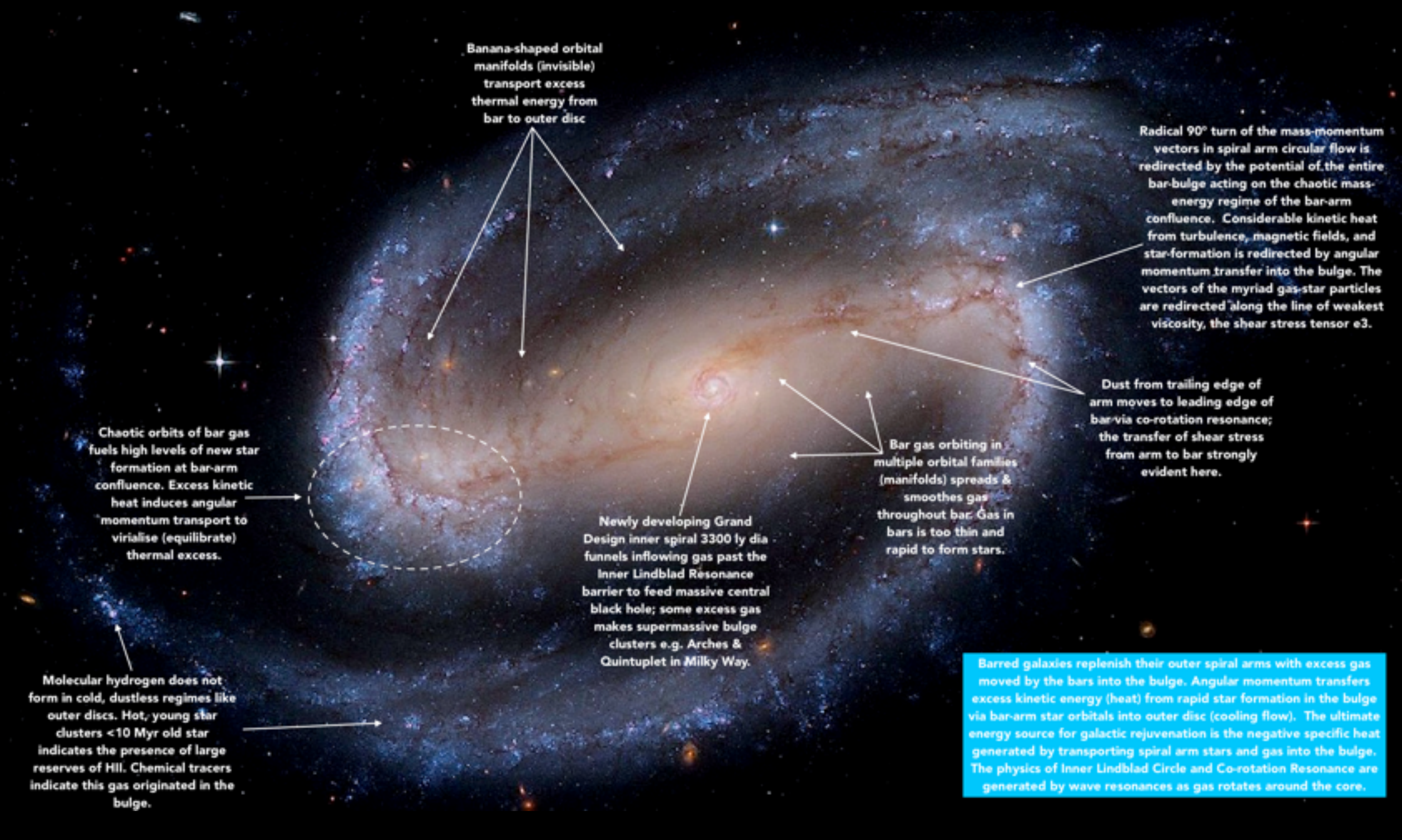


Fig. 42: Banana-shaped stellar orbitals are not related to the x_1 family orbitals shown above that traverse a galactic bar. Instead, they move rather aimlessly in the interarm region until either captured at one of the Lagrangian points, or escape into the outer disc as part of the galaxy's angular 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



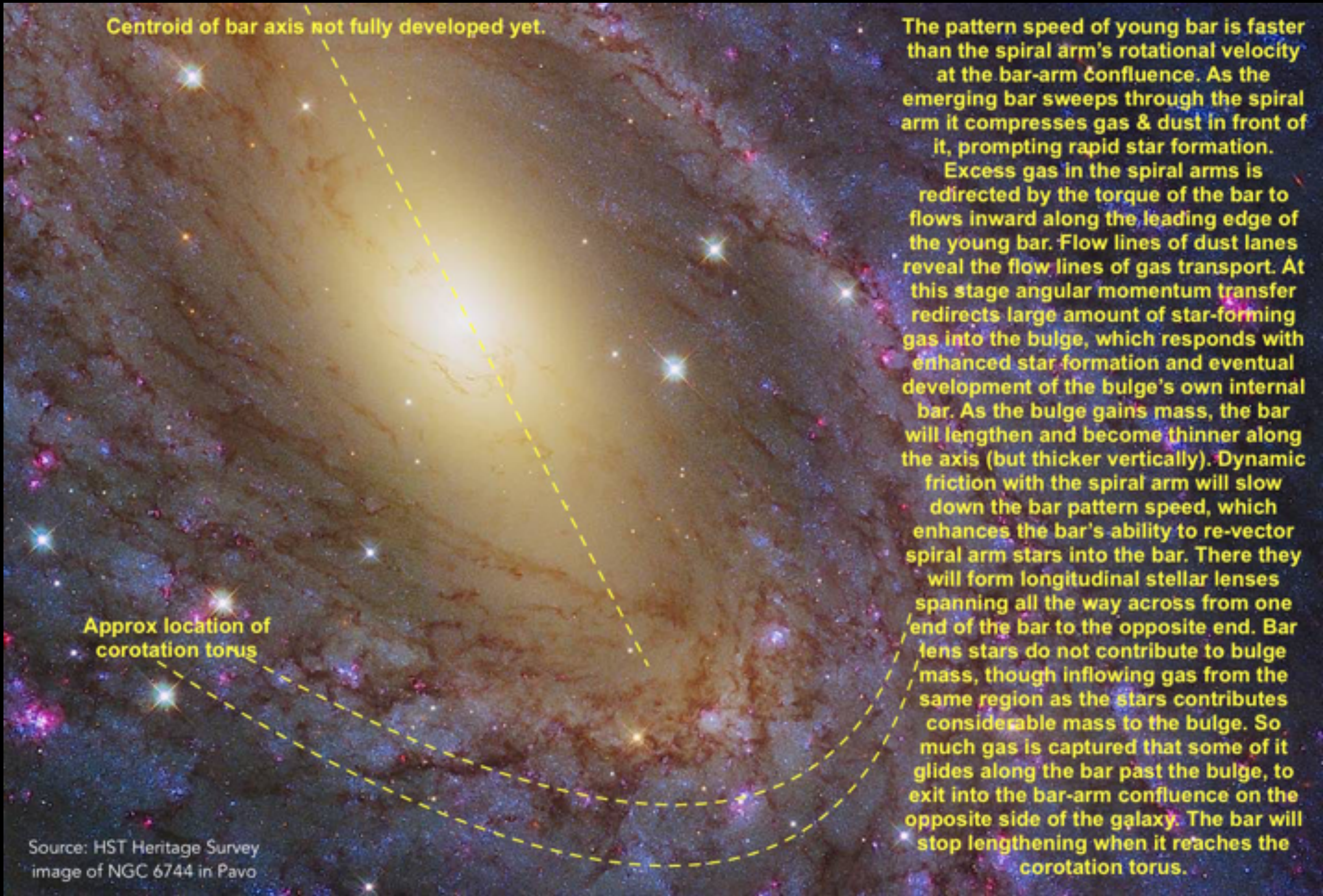
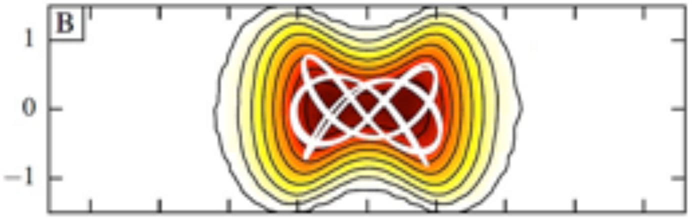


Fig. 44: NGC 6744 is in the early stages of developing a bar. Until about 300 to 500 million years ago it was a normal spiral galaxy. Spiral arms do not deliver much gas into the core of a galaxy and the bar-arm connection is both weak and fragile. A rotational Kelvin-Helmholz instability caused "pimples" 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.

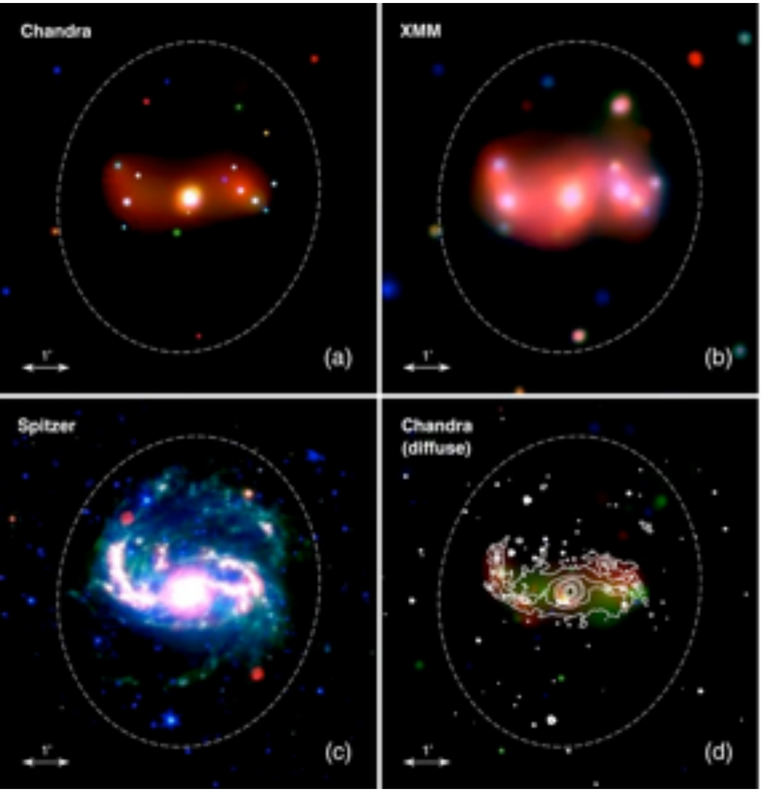


Fig. 45: As a prototype of a barred spiral galaxy, NGC 1672 in Doradus differs from normal barred galaxies in that it has two sets of spiral arms with a truncated bar joining the inner spiral to the outer disc. NGC 1672 evidences intense star formation in both the inner core bar and in the four outer 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.

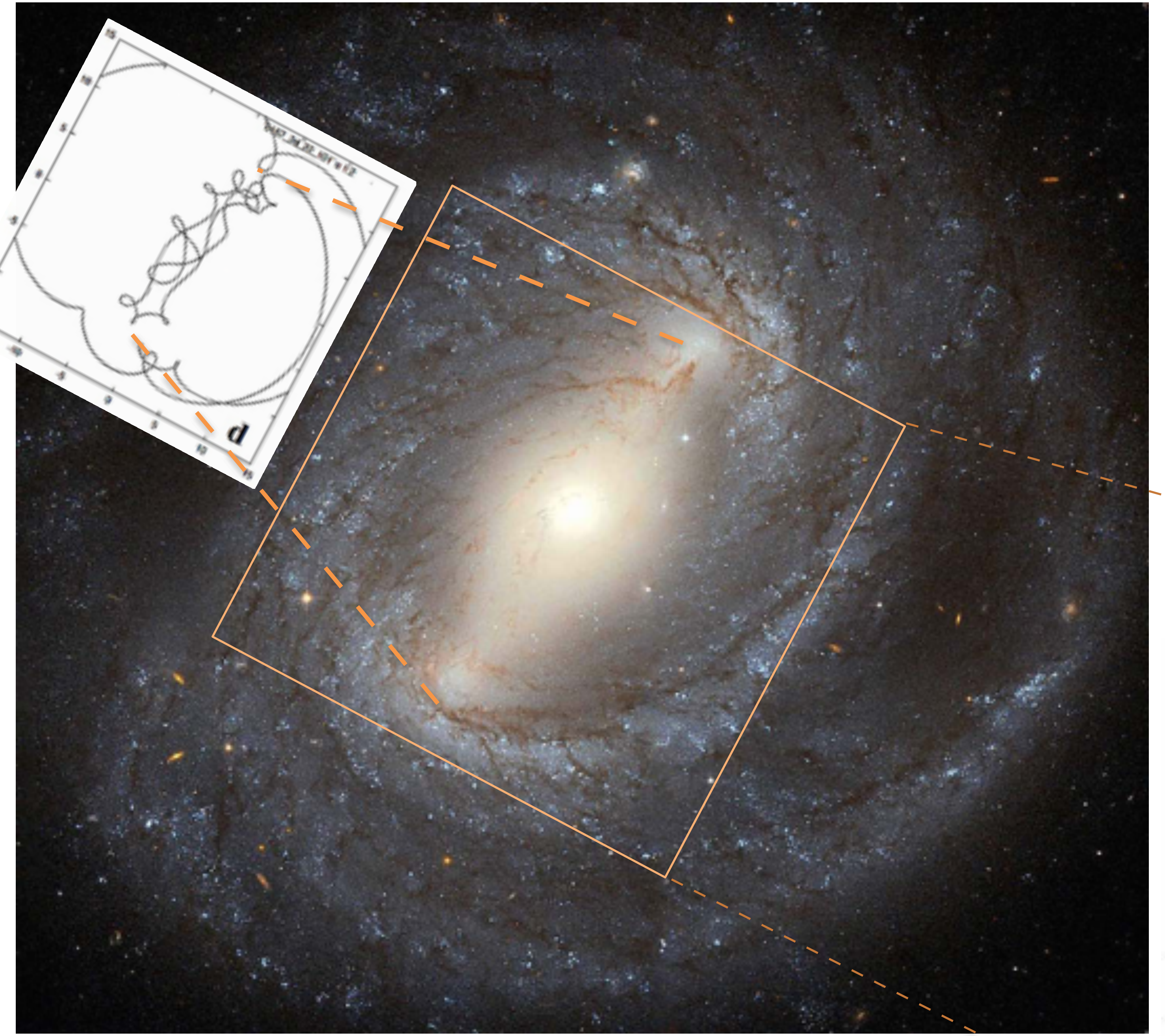


Fig. 46: NGC 4394 is a remarkable galaxy in Coma Berenices which is too often overlooked in favour of nearby giant M85. The small spike-like dust feature in the upper bar plus the the two small “bulbs” in the bar-arm confluence indicates that N4394 is undergoing an *ansae* (“wings”) phase of early bar 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.

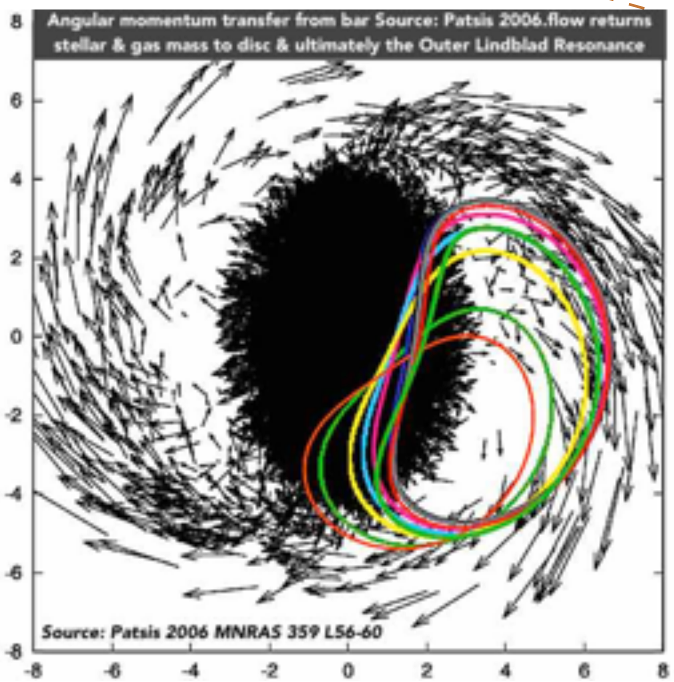
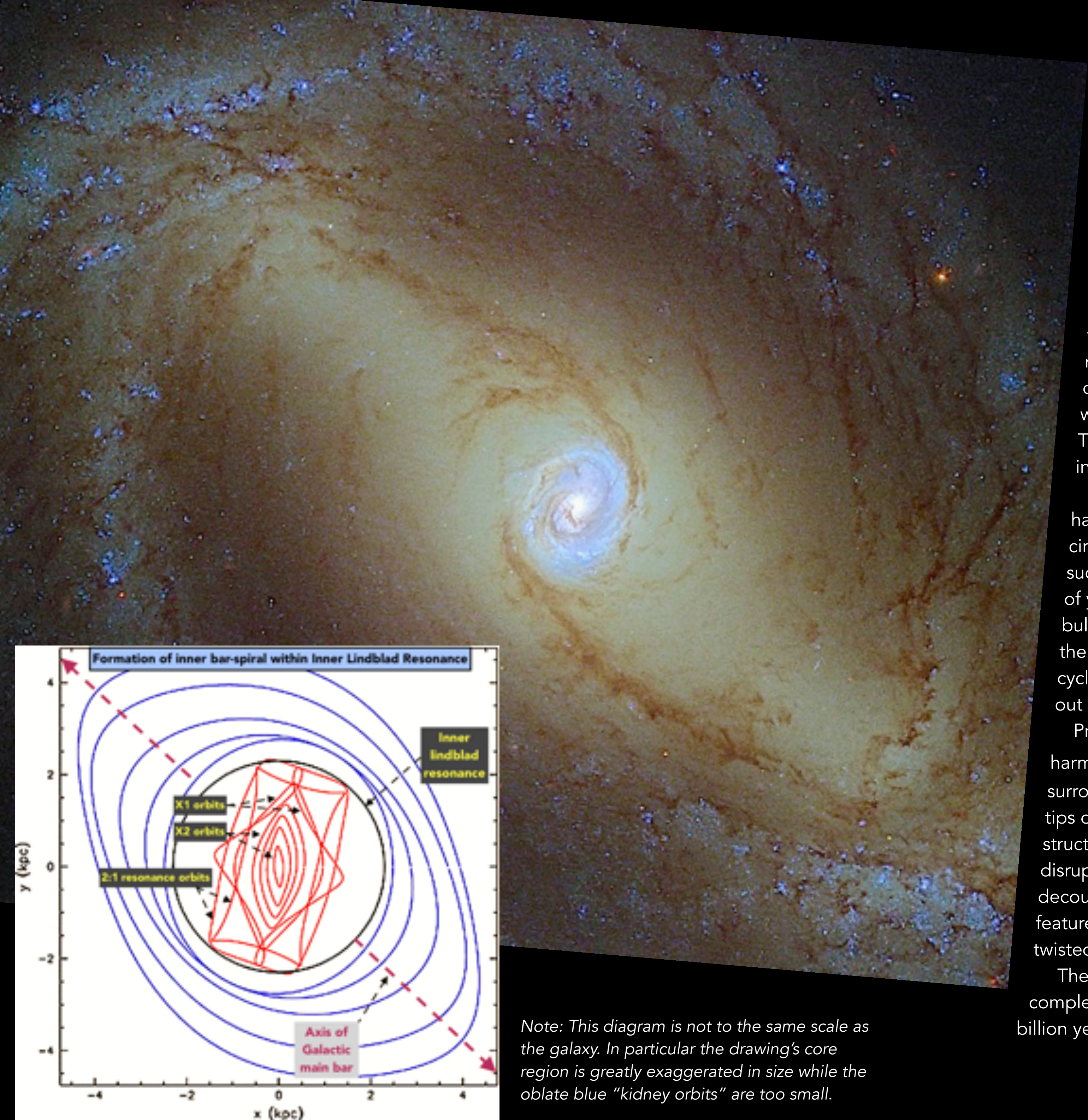


Fig. 47: NGC 3081 in Hydra, some 26.4 Kpc (86 million ly) from us, is a Type II Seyfert galaxy characterised by a dazzling high-energy nucleus powered by an actively accreting supermassive black hole. The dusty centre outlines a inner bar-spiral that evolved outwards from the core from a supernumerary 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. 48: 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. 49: 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.

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ISSN 2617-7331