NIGHTFALL

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NIGHTFALL

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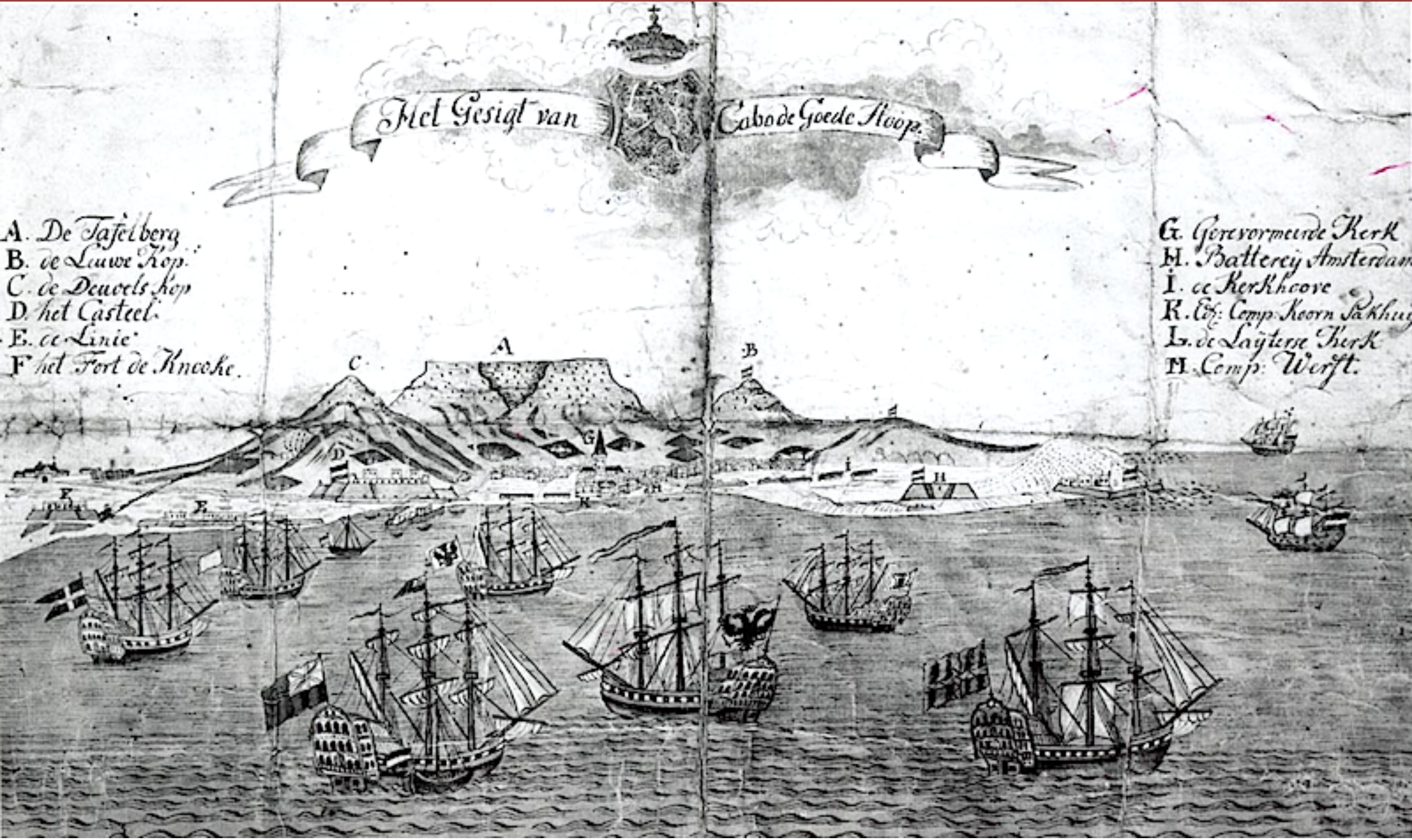
In this issue

Art: *The Sky at the End of the Road*, courtesy of Carolyn Lamunière



View of Cape Town in 1689.

A Visit to Historical Cape Town

We don't always realise how important astronomical history – the research, the nurturing and appreciation, and above all conserving and preserving it – is. It is reassuring to know that there are deep thinkers who put in much effort and do all within their power to keep such history alive.

One such a person is Auke Slotegraaf. He digs deep, and he freely and willingly shares his comprehensive knowledge with all who are interested in the subject. To have been able to spend a full day with Auke, a few years ago, on this epic journey was a privilege indeed. Auke and I looked up the old haunts of our fathers in the world of astronomy during this visit in Cape Town. And Auke and I know how to socialise! We chatter endlessly, unravelling every facet of astronomy as we go along. We would stop every so often to drink some strong coffee; and of course, there's always Auke's ritual: taking out his tobacco, rolling his own cigarette and then smoking it with leisurely enjoyment.

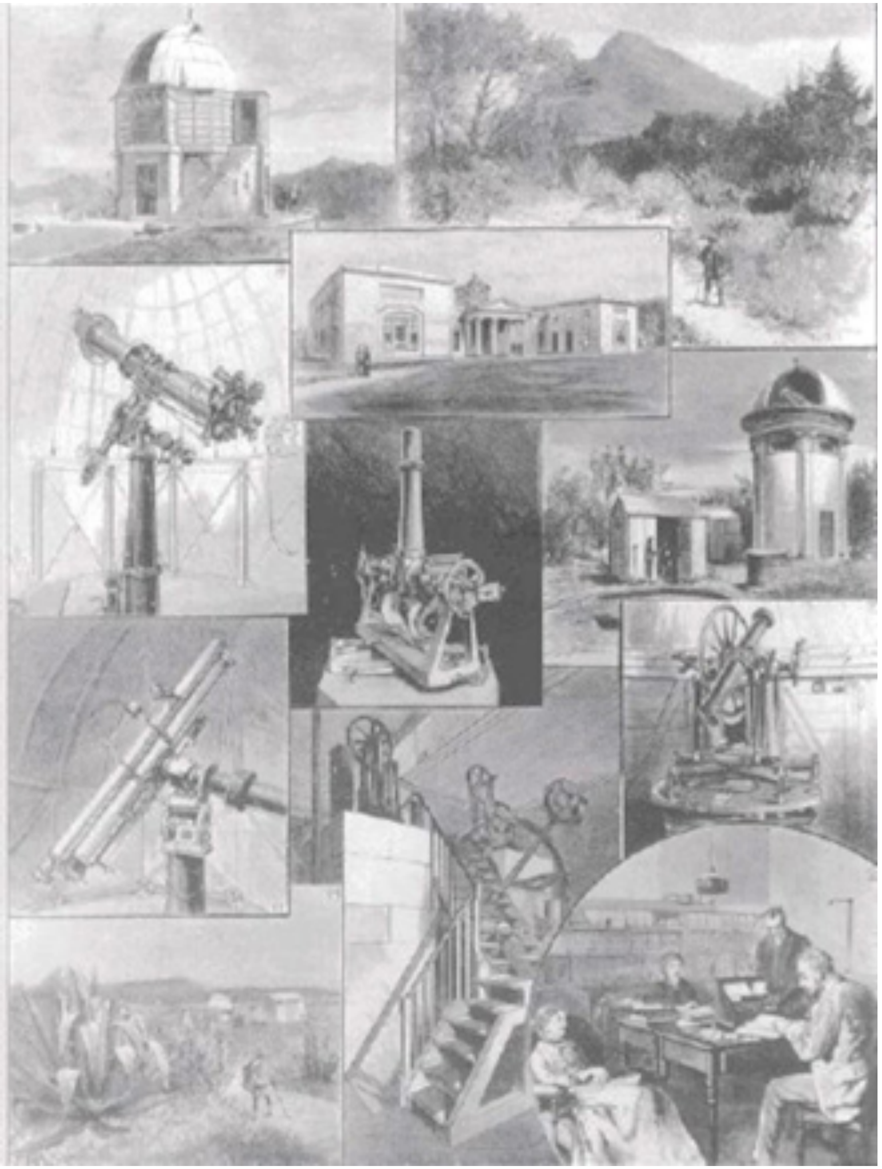
Our first stop was Herschel Street, where I had to cling for dear life to the pole bearing this special street name so that the strong Cape wind didn't sweep me all the way down the road. Just to be in the area knowing that some of the first astronomers on South African shores worked and wandered – and wondered – here brought a sense of nostalgia with it.

The end of the tram line c. 1890. The peak in the background is Signal Hill, which at one time had a semaphore on top to signal the arrival of sailing ships. The hour of noon every day was announced by the boom of a cannon fired at the top of the hill.

Map in hand (I'm no good at keeping my direction!) we made our way to the suburb of Claremont, where John Herschel lived during his stay in the Cape from 1834 to 1838. Once around the block ... and a second time ... before stopping at Grove Primary School, on whose grounds Herschel's home and observatory once stood.

The school proudly displays its astronomical roots, with images of stars and signs referring to Herschel. An obelisk erected in Herschel's honour stands prominently in front of the school. The obelisk was built around the original marble stand on which Herschel's telescope was mounted and his initials are engraved. At Auke's insistence I went down on hands and knees and crawled inside (fortunately I'm small enough) to be able to get a closer look at the initials on the pier inside the obelisk.

The entire area, and especially Table Mountain, produced a certain nostalgia in us. John Herschel's stay at the Cape of Good Hope must have



Montage of images of the Cape Town Observatory in the late 1800s in the archives of the South African Astronomical Observatory. Image courtesy of ASSA.

Magda Streicher visits the historical Herschel Road in Cape Town, named after John Herschel, who resided near today's Cape Town Observatory 1834–1838 to compile his survey of the Southern stars. Image by the author.

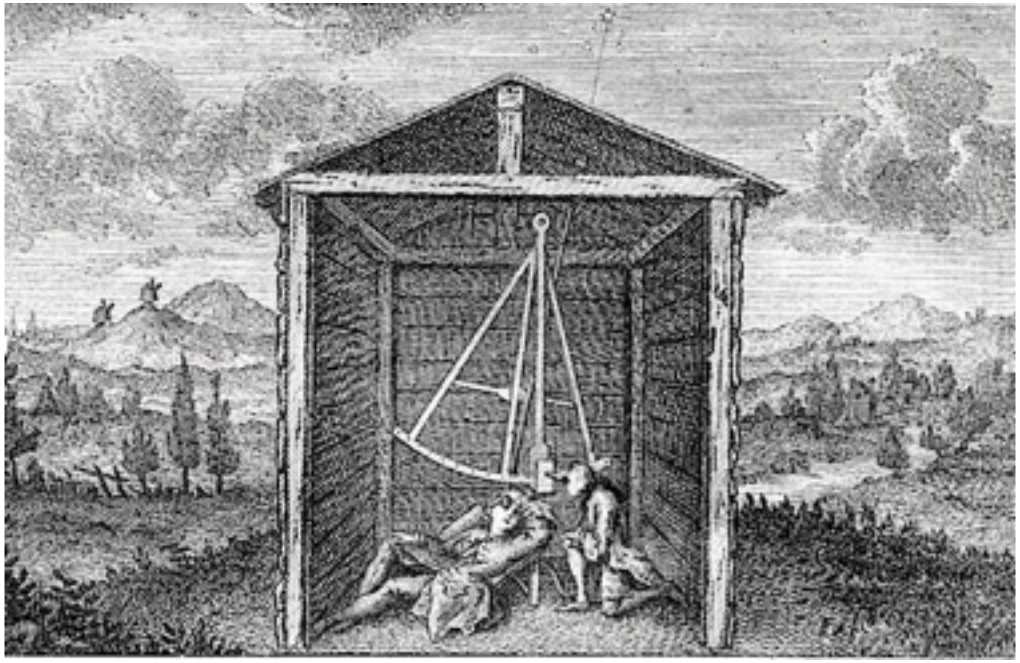
been a high point in his life, with that magnificent view of Table Mountain and a then pristine star-saturated southern night sky.

Sir John Friedrich William Herschel, the only son of William Herschel, was born on 7 March 1792 at Slough near Windsor Castle. John Herschel spent the years 1834 to 1838 surveying the southern stars from the Cape of Good Hope. It was his aim to finish the enormous work his father had started. He published a consolidated catalogue of over 5 000 nebulae and clusters. He died at his home in Kent, United Kingdom, on 11 May 1871 and was buried in Westminster Abbey.

Without doubt the high point of the day was the visit to the Cape Town Archives where John William Herschel's hand sketches of Eta Carinae. As if handling a baby, with utmost care Auke paged through this old worn volume, the yellow pages telling a story without words that leaves one with a sense of wonder. The notes in Herschel's own handwriting are like holy ground which should not be touched. It reminded me of how we make notes during work sessions at a telescope – irreplaceable. The smell of paper hung heavily in the old building, transporting our thoughts back to times long since gone. It must have been such an amazing experience for them to explore and drink in the wonders of the southern skies.

Abbé Nicolas-Louis de Lacaille (1713–1762) was the most famous French observer of his time. He came out to South Africa in 1750, mainly to determine whether the earth was round, and conducted a major geodetic survey in the Swartland to check this. He also measured the positions of 9 766 stars and named 14 new constellations. In particular from his site at the foot of Table Mountain near present-day Cape Town he named one of these Mons Mensa, the Latin name for Table Mountain. Mensa is the only constellation named for a terrestrial feature.

Lacaille published the first real deep-sky catalogue in 1755. He observed with a mural quadrant equipped with a telescope with a 0,5-inch aperture and a magnification of 8X from 1750 to 1753 at the Cape of Good Hope.



La Caille (lying) and Cassini de Thury making a latitude measurement during the survey of the Paris Meridian. La Caille used the same instrument in the Swartland of the Cape (from Cassini de Thury, 1740). Source: *Nicolas-Louis de la Caille Astronomer and Geodesist by I.S. Glass*. Oxford University Press, December 2012, ISBN 978-0-19-966840-3.

A plaque was erected in 1903 by the South African Philosophical Society, the first name of the current Royal Society of South Africa. It was designed by the famous architect Sir Herbert Baker. In 1977 the plaque was replaced on a pillar at the entrance of the Exchange Place just around the corner. When the entrance was closed the plaque was moved to its final position at the corner of Exchange Place and St Georges Street/Mall (Cliff Turk). Fortunately, Chris de Coning drew our attention to it. Nicolas-Louis de Lacaille lived in the house of Mr Bestbier in Strand Street, where he set up his observatory (Dr DM Kilkenny). Today Strand Street is a hustle-bustle of people and many eating-places. Lacaille's residence no longer exists.

Plaque commemorating Abbé Lacaille's residence in the Cape of Good Hope between 1750 and 1753. Image courtesy of the Astronomy Society of South Africa (ASSA and the good graces of ASSA's Chris Coning.

The copper plaque was badly tarnished, with green lichen all over it, making it almost impossible to read. Auke got stuck in with some water and a cloth and tried his best to clean the beautiful antique piece.

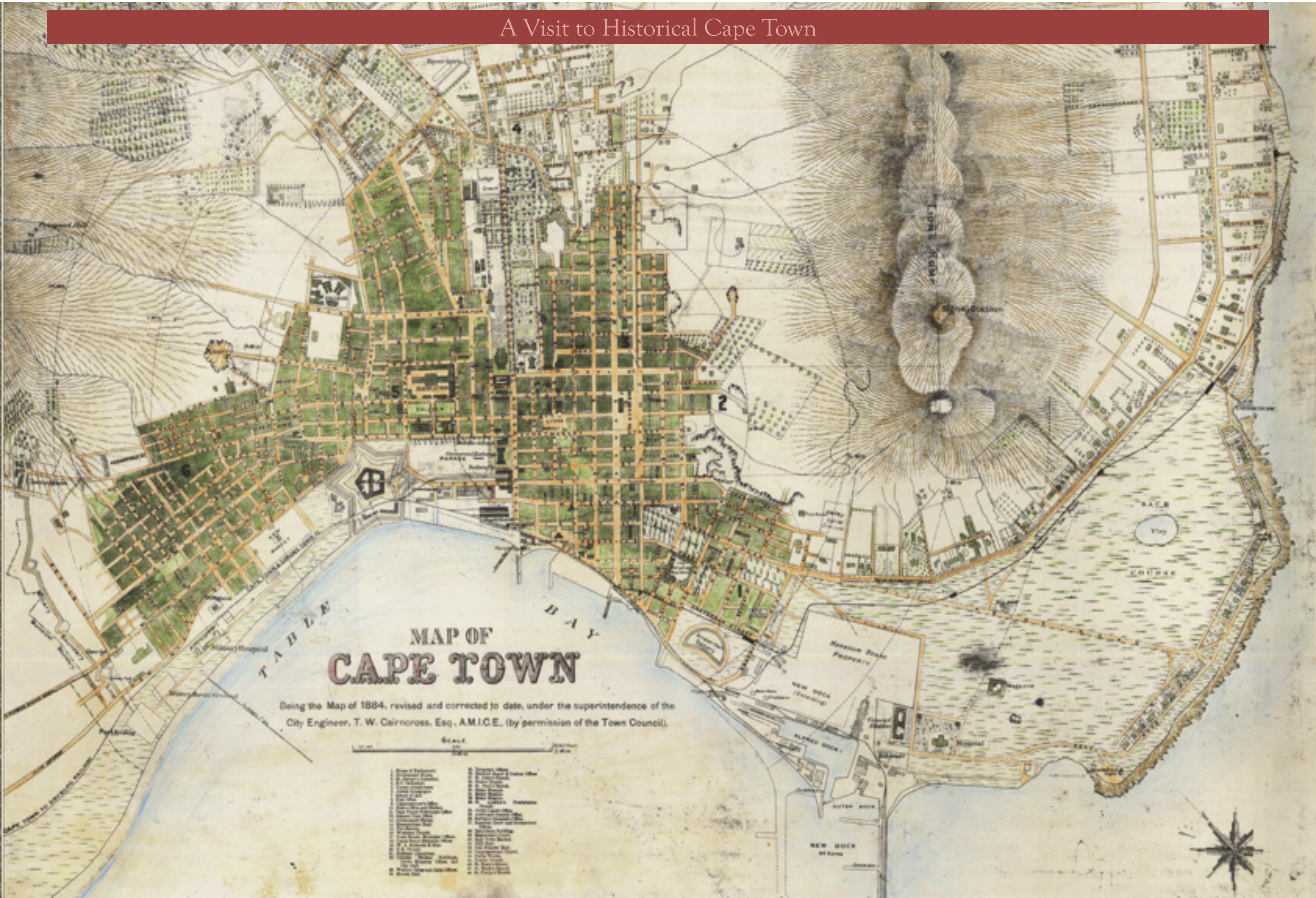
Sadly, this historically important plaque relating to Nicolas-Louis de Lacaille and the history of astronomy in South Africa was stolen on 17 March 2010 from its site at the corner of Waterkant Street and St George's Mall in Strand Street – probably to be sold as scrap metal.

Lacaille named 14 obscure southern constellations:

- Antlia Pneumatica, the Air Pump
- Caelum, the Engraving Tool
- Circinus, the Geometer's Compass
- Fornax Chemica, the Chemist's Furnace
- Horologium Oscillatorium, the Pendulum Clock
- Mons Mensa, Table Mountain
- Microscopium, the Microscope
- Norma et Regula, the Level and Square
- Octans, the Octant
- Pictor, the Painter's Easel
- Pyxis Nautica, the Ship's Compass
- Reticulum Rhomboidalis, the Eyepiece Reticule
- Sculptor, the Sculptor's Workshop
- Quandrantid, which did not last.

With the shadows slowly lengthening we sat pensively at the Livingstone Memorial on the slopes of Table Mountain as we collected our thoughts and reviewed the day. More coffee, and as Auke slowly, and in his unique way, enjoyed another smoke, we remembered the two great fathers of astronomy and their enormous contribution to the science in South Africa. Thank you, Auke, for be a long-time friend; may we share and talk astronomy endlessly for many years to come.

= *Magda Streicher.*


MAP OF
CAPE TOWN
Being the Map of 1884, revised and corrected to date, under the superintendence of the City Engineer, T. W. Cairncross, Esq., A.M.I.C.E., (by permission of the Town Council).
SCALE
TABLE BAY
RACE COURSE
NEW DOCK
ALFRED DOCK
Signal Station

Two Mighty Rivers by Susan Young

The mighty Orange River, the river of the desert, is staggeringly beautiful and life-giving as it flows through the inhospitable and desolate Kalahari. Its riverbanks are spectacularly lush and green, and contrast dramatically with the desert's red sands and scrubby vegetation. And with the pristine star-laden desert skies, it's a magical place for camping with one's dog and telescope while on a ramble around the Kalahari looking at the stars.

The Orange River is the longest river in South Africa – it rises in the Lesotho Drakensberg Mountains at an altitude of 3,000 metres, a mere 195 kilometres from the Indian Ocean. Yet it flows in completely the opposite direction – coursing westward through desert and semi-desert for over 2,250 kilometres to empty into the Atlantic Ocean at Alexander Bay. A wide, slowly meandering river, its nature changes completely downstream from the town of Upington, where it stops its gentle meandering and thunders over magnificent waterfalls and rapids, and through spectacular gorges it has carved out of the harsh rock-landscape on its journey to the sea.

The river thundering 60 metres over the Augrabies Falls into a 240 metre deep gorge

One would be forgiven for thinking its name came from the colour of the water which, during floods, turns gloriously orange from its banks' iron-oxide. But the river was named in honour of the Prince of Orange in 1779 by a Scots officer in the service of the Dutch East India Company.

The Orange River is also known as the "River of Diamonds". In 1867, the first diamond discovered in South Africa, the *Eureka Diamond*, was found near Hopetown on the Orange River. Two years later, the 47.69 carat *Star of South Africa* diamond was found in the same area, and by 1870 more than 10,000 diggers of all races, creeds and nationalities were searching for the precious little stones. But the wealth in the river didn't compare to the treasure underground, and in 1871 the river's diamond rush was eclipsed by the rush to mine diamonds directly from kimberlite at Kimberley - although the final reaches of the Orange River and the beaches around its mouth are rich in alluvial diamonds, and still mined today.

Star of South Africa

It is the most wonderful river for swimming – no crocs, no hippos, no bilharzia… just the vast river flowing through a desert to the sea. By day, one can float down the river of diamonds…and by night, float down another river of diamonds… the mighty Eridanus that flows from the foot of Orion to the beautifully named Achernar – the star at the end of the river. Like the Orange River, Eridanus is also a long meandering river with spectacular riverbanks full of galaxies, beautiful stars and mist-shrouded mysteries… which I explored with my 16" f/4.5 Dobs.

Image credit NASA

IC 2118 Reflection Nebula - Witch's Head

$05^h06^m54.0^s$ -7°13'00"

Diam 180" x 60"

What a lovely start to my journey along this mighty river – a shoreline clouded in a faint hazy mist. This faint reflection nebula glows primarily by light reflected from Rigel (located just outside the top right corner of the image). In this pristine dark sky, the nebula shows as a very large, very faint NW-SE ribbon of light; patchy and uneven, its edges misty and ill-defined. Averted vision brightened it up subtly, allowing it to stand out nicely compared to the background sky brightness. The brightest section is centered 70' ENE of mag 4.8 Psi Eridani (itself a pretty bluish-white star) and shows as a soft arc of brighter nebulosity. No sign of the witch's head outline in the nebulosity, just the faint ribbon of misty light washing the banks of this beautiful river.

NGC 1535 Planetary Nebula

04^{h}14^{m}15.8^s -12°44'21"

Mag 9.6 Diam 51" Mag cent * 12.1

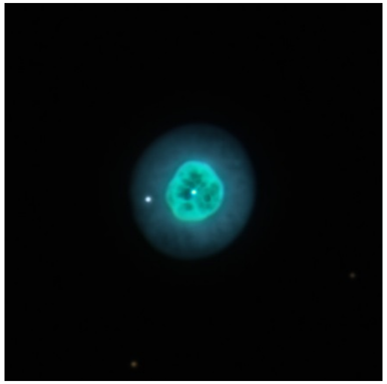
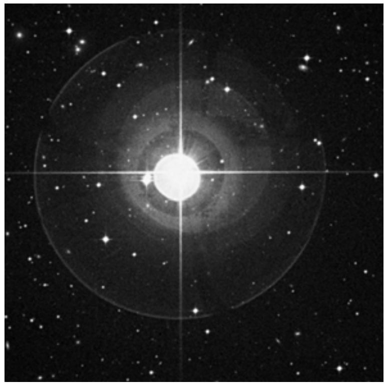


Image credit Hubble

Observing a planetary nebula is simply awe-inspiring… looking at a star dying in the night sky, its shroud of cast-off gas forming one of the most beautiful objects in the cosmos. And when one can see the dying star's exposed core - the incredibly hot, tiny white dwarf - lying at the centre of the bubble of glowing gas, and illuminating the ghost of its former self in spectacular colours and shapes, my awe knows no bounds. This little planetary nebula is an absolute beauty; standing out superbly against the starry background. It is small, bright, round and with a beautiful double-shell structure - a gorgeously greeny-blue little disc surrounded by a faint, cloudy, palest grey outer shell. Its 12.1 mag central star was clearly visible… a tiny silvery grey star, and averted vision showed a few tiny dark flecks around the little star. Superb!

40 Eridani (Omicron^2) Triple Star

04^{h}15.2^m -7°39'



DSS image

Here's a cool fact… Mr Spock hailed from the planet Vulcan which orbits 40 Eridani. Mr Spock's sun aside, this is surely one of the most fascinating systems. A true rarity: a genuine, gravity bound triple star. And even more rare, all three stars are different dwarf stars: the primary is one of the very few class K dwarfs visible to the naked eye; "B" is a 9th magnitude white dwarf; and "C" is an 11th magnitude red dwarf, as well as having another characteristic that sets it apart from most stars in the sky – it's a flare star. Could there be anything more fascinating to look at in this gorgeous celestial river? The primary is a beautiful warm yellow; the tiny white dwarf is a dull greyish-white; and the red dwarf is a tiny little drop of orangey-grey starlight. (Interestingly, Ernst Hartung described the primary as orange-yellow and the other two as both indigo-blue.) It's fascinating to peer through one's telescope at these three stars and think about what's going on up there with each of the stars…what has gone before…and what's going to happen in the far distant future. (Plus imagining the Vulcan sky with these stupendous suns.)

NGC 1300 Galaxy Type SB(rs)bc I

03^{h}19^{m}41.3^s -19°24'36"

Mag 10.4 Dim 6.2'x4.1' SB 13.8 PA 106

Image credit ESO

This gorgeous galaxy is a classic example of a barred spiral… but alas for its low surface brightness… albeit appearing fairly large, it was pretty faint, misty, diffuse, and I only got a glimpse of one of its immense swirling arms - I could see the start of the spiral arm at the west end of the bar, a faint but definite curve to the north that faded rapidly. The galaxy is elongated roughly E-W; the faint glow of the bar extending the length of the major axis, and brightening to a small but fairly bright oval glow in the centre.

Image credit ESO

NGC 1232 Galaxy Type SAB(rs)c I-II
$03^h09^m45.1^s$ -20°34'47"
Mag 9.9 Dim 7.4'x6.5' SB 13.9 PA 108

NGC 1232A Galaxy Type SB(s)m IV
$03^h10^m02.1^s$ -20°36'01"
Mag 14.6 Dim 0.9'x0.7' SB 14.0 PA 5

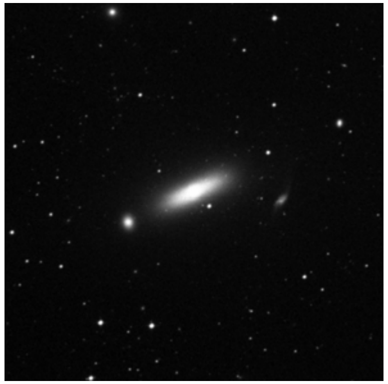
NGC 1232 has a bright, large, oval core and a faint stellar nucleus, surrounded by a large, very much fainter and diffuse halo - a soft glow of misty light. Averted vision displayed a slightly misty edge, and a few flecks of slightly brighter brightness across the surface of the galaxy. I could see what I suspect was the start of a spiral arm attached at the west end of the core - a faint glow curving towards the east on the north side of the core, but it faded rapidly into the overall mistiness of the halo. Small, dim NGC 1232A is located on the eastern edge of the galaxy; I looked long and hard for it, but wasn't able to see it.

DSS image

NGC 1532 Galaxy Type SB(s)b pec sp I-II
$04^h12^m02.5^s$ -32°53'01"
Mag 9.8 Dim 12.6'x3.0' SB 13.6 PA 33

NGC 1531 Galaxy Type SO$^-$ pec:
$04^h11^m59.0^s$ -35°51'04"
Mag 12.5 Dim 1.3'x0.7' SB 12.3 PA 122

NGC 1532 is a superb edge-on galaxy, made striking by the faint oval glow of its small companion, lying situated just 1.7' NW of its core. It appears as a bright, large, highly elongated NE-SW slash of light with a bright bulging little core and beautiful pointy ends that fade into the sky. With averted vision, the halo is subtly mottled, and I also caught a very shadowy glimpse of the dust lane that extends along the major axis, just SE of the core. NGC 1531 appears as a faint, very small, very diffuse and even oval-shaped NW-SE glow of light.

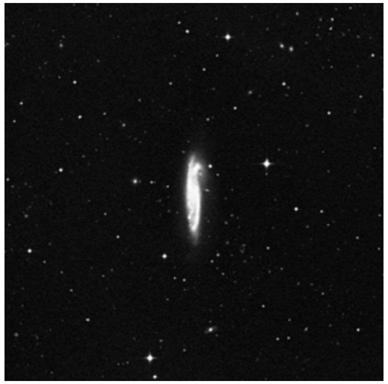


DSS image

NGC 1332 Galaxy Type S(s)0: sp
$03^h26^m17.0^s$ -21°20'06"
Mag 10.3 Dim 4.5'x1.4' SB 12.2 PA 112

NGC 1331 Galaxy Type E2:
$03^h26^m28.3^s$ -21°21'19"
Mag 13.4 Dim 0.9'x0.7' SB 12.9 PA 3

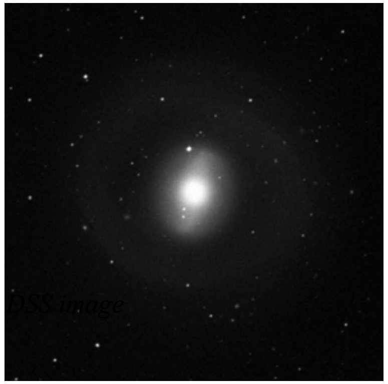
Another edge-on galaxy with an interestingly placed companion! NGC 1332 appears as a bright, moderately large oval, elongated NW-SE. It has a small bright core, and its halo is a silky diffuse glow with softly rounded edges. A faint star lies just SW of the core. NGC 1331, lying off its SE end, appears as a faint, small, round glow.



DSS image

NGC 1421 Galaxy Type SAB(rs)bc: II-III
$03^h42^m29.3^s$ -13°29'25"
Mag 11.4 Dim 3.5'x 0.9' SB 12.5 PA 0

This is a lovely edge-on galaxy - a moderately large slash of beautiful bright-ish light, very elongated N-S. It has a bright core, and with averted vision I can pick up the slightest hint of bulging in the core area. The surface, also with averted vision, has a few very subtle hints of mottling, and fades into the dark sky towards both tips. The northern edge, which has a 12 mag star lying off its western tip, appears marginally brighter than the southern edge, which itself appears to have a very slightly fuzzier look to its edge than the northern end.



DSS image

NGC 1291 Galaxy Type (R)SB(s) 0/a

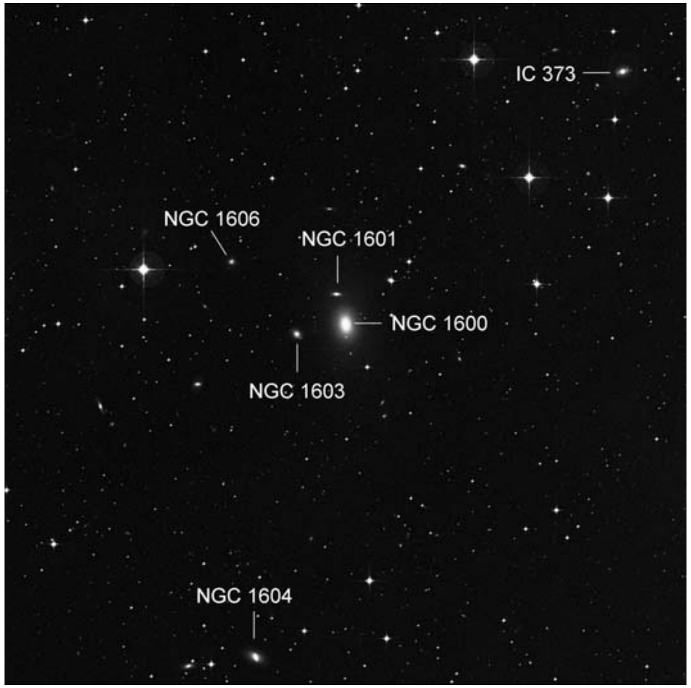
$03^h17^m18.7^s$ -41°06'00"

Mag 8.5 Dim 11.0'x 9.5' SB 13.4 PA 72

NGC 1291 (also known as NGC 1269) is a fascinating galaxy - a ring galaxy with an unusual inner bar and outer ring structure. Alas, I could see no sign of the faint ring so tantalizingly visible in the DSS image. What I did see was a very bright, moderately large, round core, with an almost stellar nucleus. The core has diffuse edges that dissolve into a large, faint, oval mistiness that surrounds it.

NGC 1600 Group

It's always an enjoyable observing experience to look at a group of galaxies, and the NGC 1600 group is no exception. A widespread group, I observed it in two sections, beginning with NGC 1600 and the five galaxies around it:



DSS image annotated 25'x25'

NGC 1600 Galaxy Type $E3^-$

$04^h31^m39.9^s$ -05°05'10"

Mag 10.9 Dim 2.5'x1.7' SB 12.5 PA 15

This is the brightest and largest galaxy in the group, and it appears as a bright, moderately large oval, elongated N-S. It has a bright core, and an almost stellar nucleus. The halo appears as a smooth, even glow. It forms a nice trio with NGC 1601 which lies 1.6' N, and NGC 1603 lying 2.6' ESE.

NGC 1601 Galaxy Type S0: sp

$04^h31^m41.^s7$ -05°03'37"

Mag 13.8 Dim 0.7'x0.3' SB 12.0 PA 90

Located off the northern edge of NGC 1600, this galaxy is a very faint, extremely small, slightly-off round glow.

NGC 1603 Galaxy Type E?

$04^h31^m49.9^s$ -05°05'40"

Mag 13.8 Dim 0.8'x0.6' SB 12.8 PA 37

This third galaxy in the close trio appears as a very faint, very small, round droplet of pale light.

NGC 1606 Galaxy Type $SAB(r)0^+$:

$04^h32^m03.3^s$ -05°01'57"

Mag 14.9 Dim 0.5'x0.5' SB 13.2 PA -

I could only see this galaxy with averted vision, and it was an extremely faint, extremely small, round bead of fuzzy light; almost stellar.

NGC 1604 Galaxy Type S0

$04^h31^m58.6^s$ -05°22'12"

Mag 13.7 Dim 1.2'x0.8' SB 13.5 PA 71

Lying 17' S of NGC 1600, this galaxy was very faint, very small, slightly off-round. Averted vision revealed a very slight brightening to the centre.

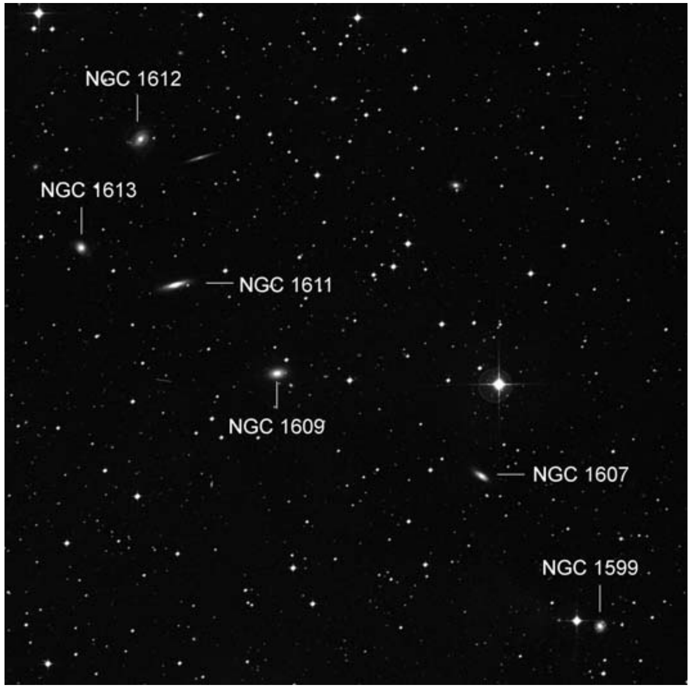
IC 373 Galaxy Type $(R)SB(rs)0^+$

$04^h30^m42.7^s$ -04°52'13"

Mag 13.9 Dim 0.8'x0.8' SB 13.3 PA -

19' NW of NGC 1600, this galaxy is an extremely faint and small round glow.

In this DSS image, these other members of the NGC 1600 group form a lovely meandering chain of galaxies, but when it comes to observing them they are very faint, and very small! Fortunately, I had excellent conditions which made all the difference. I began with NGC 1599… an easy hop west of the mag 9.1 star, SAO 131769.



DSS image annotated 25'x25'

NGC 1599 Galaxy Type SB(s)c pec: II-III
$04^h31^m38.7^s$ -04°35'18"
Mag 13.7 Dim 0.9'x0.8 SB 12.9 PA 174
This galaxy appears as a very faint, extremely small, round little droplet of fuzzy light.

NGC 1607 Galaxy Type S0/a
$04^h32^m03.1^s$ -04°27'37"
Mag 13.2 Dim 1.2'x0.5' SB 12.6 PA 50
This galaxy appears as an extremely faint, very small, very slightly off-round glow.

NGC 1609 Galaxy Type (R')S0$^+$ pec:
$04^h32^m45.1^s$ -04°22'21"
Mag 13.5 Dim 1.3'x0.8' SB 13.5 PA 95
This galaxy was extremely faint, very small, very slightly-off-round and averted vision revealed an very slight brightening to the centre.

NGC 1611 Galaxy Type (R')SB(rs)0$^+$ pec?
$04^h33^m05.9^s$ -04°17'49
Mag 13.4 Dim 1.9'x0.6 SB 13.4 PA 108
This little galaxy was a very faint, very small, thin, very elongated WNW-ESE slash of light. Averted vision revealed it brightening very slightly to the centre.

NGC 1613 Galaxy Type SAB(rs)0$^+$?
$04^h33^m25.3^s$ -04°15'55"
Mag 13.7 Dim 1.1'x0.7' SB 13.2 PA 45
This galaxy appears as a very faint, very small, round glow that, with averted vision, brightens very, very slightly to the centre.

NGC 1612 Galaxy Type SB(r)0?a
$04^h31^m13.1^s$ -04°10'24"
Mag 13.4 Dim 1.3'x1.0' SB 13.5 PA 142
This galaxy appears as a very faint, very small, round glow. Averted vision revealed a very slight brightening to the centre.

I rounded off my trip along this dazzling river of stars with Achernar, the star at the end of the river. To my eye, it is one of the most gorgeous stars in the night sky. In the telescope it burns with the same ice cold bluey-white fire of the Orange River's famous *Star of South Africa* diamond.

Paranal Unit 4 on a moonlit night <https://cdn.eso.org/images/screen/potw1038a.jpg>

Cool fun

It's OK to have fun with the Universe, too

SOLAR SYSTEM SCOPE

Here's a great one for the kids (including me!): an online interactive model of the Solar System — planets, asteroids, and of course the star of the show, our Sun in beautiful golden yellow. *SSS* is a multilayer infographic that you can rotate in any direction and zoom in or out while you do. It begins with an opening Grand Tour sequence showing the planets and their moons up close (Saturn is spectacular). You can stop the Intro at any point by clicking anywhere on the screen. The model switches to a view of the Sun and inner planets, all spinning like tops with the Moon scooting around the Earth. The orbits are shown as white ellipses, and the whole thing sits in 3D space above an image of the background stars with the constellation lines marked. Mouse-scroll the cursor one way or the other (or move the slider bar on the right edge) and you fly through the solar system with your mouse as the control stick. You also can rotate the Solar System in any plane, from the planets all lined up in a disc to looking down everyone's polar axis. Zoom out so the Asteroid Belt in on the screen, rotate to the disc plane, and move the cursor to spin up the Solar System's rotation. The asteroids whiz by so big and so fast that you want to duck.

The background stars change as you rotate. On the left edge is a 3-compartment box where you can change viewing options, use a settings panel to decide the objects you want most — planets, dwarf planets, comets, outer planets — you get the idea. The top box, with a tiny model of the inner planets, open to a list with five choices, Solar System, Planet System, Fixed Stars, and a really keen one: Planet Explore. This one does everything the big coffee table books used to do — surface features, internal structure, moons — only now in 3D and full motion. There's an Encyclopedia entry for everything in the model.

You can also use the Outer Planets model to find out where the objects are on the sky right now. Jupiter is in Libra, that's cool. But Makemake? Haumea? Well, they are in Boötes and just above the Teapot lid (near M22, in fact). Who knew?

You can buy it as a download to install on your computer so you don't gobble up your wireless time. US$9.80. The best R116 you can buy. *Website here.*

SKY AY NIGHT FIELD OF VIEW CALCULATOR/TELESCOPE SIMULATOR

Are you sure you're looking at the right object in that eyepiece? You want M36, but how can you be sure you're not looking at M26? Or M35, M37, or M38? Or even M39, which is about as different from M36 as clusters can get. *Sky at Night* to the rescue. Their 'Field of View Calculator & Telescope Simulator' gives you a lot of options to choose from — telescope brand (Celestron, ES, etc., including some exotics like Astro-Physics and PlaneWave), diameter, focal length, etc. The Targets include Messier, Solar System, and Search. Additionally, the site has a 'Camera' list, too: Apogee, Atik, Canon, Minolta, Olympus, etc. Here the site is a bit dated because it doesn't show the trendier brands of today like SBIG.

Let's try Messier Objects using my 200mm Intes Alter F/4 astrograph (used visually for this demo). Key in the diameter and efl and a picture of the Orion Nebula inside a circle shows up on the screen box. It is indeed just about the angular dimensions it looks like in my various eyepieces. The app can't reproduce local sky conditions, so they use stock images provided by an assortment of amateur A-P'ers. Go to the eyepiece and Well I'll Be, they're *right*! That's what M42 looks like at 90x! How did they know I have 82° FOV eyepieces?

Another example: if I put an Atik 314E on that scope, I would have a 4.65 μm pixel size, 1392 x 1040 px field size, an FOV of 27.81 x 20.70 arcmin, and a resolution of 1.2 arcsec/pixel. Just the ticket for the all-in enthusiast who has five CCDs and one video cam to play with.

If you're still at the tire-kicking stage of this hobby and you don't know what equipment best suits you, *Sky at Night* thoughtfully links to their handy *Equipment Reviews* page: Dobs, Schmidt-Cass, Newts, eyepieces, cameras. Everything, that is, except where the pony up the rands to buy these things. Gee, that Explore Scientific 16" Truss Dob sure looks . . .

There is a French phrase for this moment: *lécher les fenêtres*, or 'to lick the windows'. Remember when we were kids how we used to press our noses against the shop window glass to get a better look at the Christmas goodies on the other side? No tree, sleigh, or snow needed on *Sky at Night FOV Calculator*. There's no shop window and everything is free. Bless those folks forever and ever.

MAGNIFYING THE UNIVERSE

This interactive infographic from *Number Sleuth* accurately illustrates the scale of the observable universe, ranging from a proton to molecules, insects, nebulae, galaxies, the CMB's surface of last scattering. amd even larger. From the 46-Gly whole universe down 64 orders of magnitude to a hydrogen proton that fills a quarter of the screen. Numerous 'hot points' along the zoom slider show where to access the planets section, animals, the hydrogen atom, VV Cephei, and everything else we can think of. Just about the only thing it doesn't show is the vacuum energy particle-antiparticle pairs and quantum gravity particle. As you scroll, a handy dial spins to show you your present magnification level in orders of magnitude. Nifty way to learn what logarithms actually do in reality instead of just being a number with *log* in front.

Other sites have tried to scale the universe; none has done it with quite the panache of *Magnifying the Universe*. It shows real photographs in 3D space. To fully capture the awe of the vastly different sizes of the Pillars of Creation, Andromeda, the Sun, giraffes, Kodiak bears, mice, protozoa, the rhinovirus, DNA, and the carbon atom, you really need to see pictures. How else would you discover that South Africa j-u-s-t fills the Mare Procellenarum basin on the moon? Or that the Cat's Eye Nebula is a dead ringer for coated vesicles except for the minor matter of being >4 x 10^{22} (OK, OK: more than 40,000,000,000,000,000,000,000) times larger than those microscopic sub-eensyeensy cysts that can block the interior walls of blood capillaries.

Each time you zoom in a depth, you magnifying the universe in 10x increments. very time you zoom in a notch, the new and smaller objects are 1/10th of their prior size. If you zoom from the biggest object, The Observable Universe (8.8 x 10^{26} metres across) all the way down to the hydrogen atom's proton nucleus at 1.7 x 10^{-15} (0.0000000000000017) metre across). Immensity and infinitesmal are but a slide bar away.

= *Dana De Zoysa*

Around the Universe in Eighty Sims

Remember *orreries*? They were fiendishly complicated, rather spidery constructions that modeled the motion of the Sun's planets known at the time using brass gears, spheres that might be made of anything from brass to gemstones. The spindly stilts had tiny gears inside their elbows. At one time the playthings of aristocrats and delight of astrologers, over time the fussily decorated orrery of a Baroque-era salon became more a scientific training tool. Have a look at the rich imaginations (to say nothing of technical acumen) of historical orreries *here*.
Credit: Popular Mechanics, a Hearst Publication.

If a picture is worth a thousand words, can an Astro-Sim be worth a thousand papers?

Sometimes it seems so. The output of sims is rising so fast it's hard to keep up, and they are getting more accurate and informative all the time. 'Sims' are astrophysical models of real events; they are the astronomer's version of computer-generated movie graphics. Instead of metal-plate monsters and doe-eyed nymphettes, we get magnetic fields, colliding galaxies, and even the entire history of the universe, all so realistic it turns a million years per second into something we can imagine whizzing by the window. In this instalment we present a starter-kit of primary sources — the websites that aggregate whole sim categories.

So put away the star charts for the night, off we go . . .

University of Nebraska Applet Project

Here is one fabulous learning site. The *NAAP* presents 15 sims that show us how the nuts and threads of astrophysics bolt together into real objects in real space. Here's a little sampler using just three of their applets.

First off, *Hydrogen Atom Simulator* gets us started with the primordial, and still most-common, atom that makes up the universe: Hydrogen. It takes a photon packing 13.63 electron volts (eV) of far-UV energy to fully ionise a hydrogen atom. i.e., to kick its electron clear out of the atom's many quantum energy shells. Go the applet, move the cursor on the bottom from left to right and click on 'Fire photon'. The squiggly little things enters stage right, in the colour of the energy level you have selected. Not much happens till you arrive at L_α (Lyman alpha) at 10.2 eV; below that the photons glide right on by the proton in the atom's centre. But at 10.2 eV the atom does respond, absorbing enough UV energy to boot the electron into the atom's first quantum shell. But wait a second and *spliff*, the electron releases a photon of the same energy, 10.2 eV, and the electron pops back down into the ground state. Continue firing photons along the line till you arrive at Lyman Beta (L_β)/ Not the atom absorbs 12.09 eV of energy and pops up two quantum shells. A moment later the electron emits another 12.09 eV photon and pips back down two quanta to the ground state. Finally, move the cursor to the Lyman α energy level of 13.6 eV and fire the photon. This time the atom's electron is ejected clean off the atom and whizzes off into space; the atom is fully ionised. But wait a minute, soon a random electron with an energy matching the energy level of one quantum orbit enters into the proton's cross-section for a given quantum energy and is absorbed. Things get unpredictable here. Keep firing photons and you find that the random arriving don't always get captured at a single energy shell. It depends on the energy of the arriving electron. But no matter which shell initially absorbs it, the excess energy is quickly radiated away in increments of the energy levels of each descending shell. This can be two, three, or more successive photon emissions. But the sumtotal of energies that bring the electron to the ground state adds up to 13.63 eV.

While this applet is fun to play & learn with — like shooting rubber ducks in a carnival show — it packs a couple of important lessons:

(1) the less dense the number of free electrons in a given volume of space, the longer it takes for an atom to get ionised and to de-ionise back to the ground state. Interstellar and intergalactic space can have so little matter that a cubic metre or more might have only one

or a few particles in it. But the average photon density of all space throughout the universe is 411 per cubic cm. Atoms are very tiny and photons are even tinier (or rather, their electronic charge cross sections are). That's one reason why life is v-e-r-y slow in the emptiness of space, and veryveryfast inside a star. In both conditions there are a great many ionised atoms, therefore free electrons, therefore^2 electric fields, and therefore^3 magnetic fields.

(2) the primordial universe was very young, dense, and soupy, and was expanding with only tiny differences in local densities ('local' being the size of what are today galaxy superclusters, or $10^{12}\ M_{\odot}$.) When the temperature of space finally cooled below about 8000 K and free electrons could combine with free protons into hydrogen atoms, the vast expanse of space throughout the universe became very clear very quickly.

Next, the UNAP *H-R Diagram Explorer* can tell us more about the interaction of star mass, temperature, and luminosity in 10 minutes of playing around than any 20 astro-ph papers (see right) or any 3 textbooks. The *H-R Diagram Explorer* web page opens to 2 panels. You can click on the 'cursor properties' on the left side side, or the red 'X' in the box on the right side. Move the tabs or cursor around and watch the images. Don't forget to check out what happens when you click on the 'Options' under the right-hand box. Note that you can change the *y*-axis to read *Temperature*, *Spectral Type*, or *B–V Index*, and either *Luminosity* or *Magnitude.* The term 'Magnitude' refers to *absolute magnitude* (symbol M_V) here; the subscript V means that the magnitude is measured in the visual band. If it is measured in the blue band (by using a blue filter, for example), the symbol would be M_B; M_R using a

*** *Newbie tip:*** Everybody, it seems, knows about arXiv, and just about everybody pronounces it 'archive'. Dead giveaway that you're new at this. Here's why: Anybody with any kind of street cred in the various scientific professions posts their papers on arXiv first, even if those papers have been submitted (even accepted) by the lead journals in their field. In our case those journals would the the likes of *Astronomical Journal* (A-J), *Astrophysical Journal* (ApJ), *Astronomy & Astrophysics* (AA), *Monthly Notices of the Royal Astronomical Society* (MNRAS), and a handful of others in the most-cited community. But take look at the *arXiv main page* and we find that it aggregates qualified submissions from *Mathematics*, *Computer Science*, *Statistics*, *Economics*, and four other umbrella disciplines. Take for example *Quantitative Biology.* Move your cursor across the blue-coloured phrases, and you find these are links to the 10 sub-disciplines that shelter under the umbrella term of Q-B. Click on any one of these, e.g., *Molecular Networks*, and you will quickly discover why astrophysics is s-o-o-o much more interesting. Since the professional journals have very expensive staffs to support (you practically need a Ph.D to read their toilet paper) and they cost to the skies to print, they are not keen on we freeloaders peeping about at will. But professional astronomers want everyone to have immediate access to their hard work. So they post on the freebie sites like arXiv in first-draft form. That's one reason why you see so many typos and badly constructed sentences in arXiv papers. Also, a paper that's been accepted by a professional journal gets edited. Things get changed around—especially graphs and graphics that must be updated as close to press time as possible. A paper on arXiv might be six months old by the time the up-to-the-minute professional-paper version comes out. If you say 'archive' or write 'arXiv', which one are you talking about? Working astronomers refer to the astrophysics papers as *'astro-ph*'.

red filter. (These terms are not italicised; if the the magnitude is listed in *italics* it means *apparent magnitude*, e.g., M_V, M_B, M_R).

The *H-R Diagram Explorer* an extremely handy tool if you want to reverse-engineer to a star's unknown properties by using its known ones. Let's say you read somewhere that a star has a *B–V* index of 0.8 and luminosity is 10,000 times that of the Sun. What kind of star is it? Put the red 'X' on the location of those number on the right-hand plot, and you find it's a red supergiant 100 times the diameter of the Sun and it's surface temperature is 5800 K. Over on the right-hand panel, will you look at the size of that thing compared with the Sun! You, me, and all the water on our planet would be a salty Earth Soup if that star was our Sun.

Now, go back to the right panel and click on Spectral Type and Magnitude in the Options boxes. The star turns out to be a G-type star with an absolute magnitude of –4.75. That what our Sun's going to be about 3.5 billion years from now.

Finally, if you've been scratching your head over the term *distance modulus* and get a sort of hazy, well-maybe, if–but-andsoforth idea of what it means, this *University of Nebraska applet* explains what it means and how to run the numbers, all on one page. And a *lot* clearer than the Wiki page.

Galactic Orrery sims

The idea that an orrery is a mechanical depiction of a static system has never really lost its utility. The practical scale of an orrery stops at the the solar system (although this iTunes' app does include the Oort Cloud). Making an orrery of even the Milky Way's nearby dwarf galaxy with a third dimension to include and the sheer size of the local system, a physical model is out of the picture. Yet the orrery is alive and very healthy, thanks to the computer algorithm.

The Galaxies 3D web site retains the spheres-and-rods look, but in a style that fits on on every computer screen or iPhone. Galaxies3D renders celestial objects and structures — stars, star clusters, nebulae, galaxies, galaxy groups and clusters, and superclusters — as identical-sized spheres attached via a line to a 10 x 10 grid. Although the size of the spheres and their identifying labels are uniform when the image is not rotating, they shrink or expand slightly so nearer objects are larger and farther objects are smaller. The length of each line connecting each spheres to the grid corresponds to the distance of the object above the grid.

Galaxies3D is very useful for teachers or parents of school-age kids. The combination of simple graphics and the website's creators understanding of how children like to play as they learn. Each clip runs a 4-step sequence that begins with a static 2D image, then rotates first horizontally, then vertically, and ends with a return to the home position.

There are nine different interactive models that progress outward from *Stars in 3D* (10 sims), *Star Clusters and Nebulae in 3D* (13 sims), and finally to *Beyond Our Galaxy in 3D* (5 sims).

And the best, most thoughtful part: you can download Galaxies3D

If the professional astronomy community ever gets around to an annual bow-tie-and-fashion-model gala called "Golden Galaxies Award" for the best sims and vids of the year, Galaxies3D would would be a shoo-in for a Golden Galaxy prize in Educational Astronomy.

for free so you (and your kids) don't need to be online to learn about the universe.

MHD sims

MHD is short for *magnetohydrodynamics*. It is hard to imagine a word more guaranteed to initiate a dull conversation than this one. But for hobbyist astronomers who want to understand just why the Lagoon Nebula, the Dark Doodad, Coal Sack, or Crab Nebula look like they do in the eyepiece, the word magnetohydrodynamics is Square One. All these, and many *many* more, involve the interplay of magnetic fields, electric currents, temperature, pressure, and the chemical contents of a gas. In fact, just about every object we see in the Milky Way got where it is, and looks the way it does, because of the way MHD works.

Make it easier on ourself and just use the acronym MHD. MHD sims are a big-ticket item in professional circles because a sim distills extremely complex mathematics and computer algorithms into an easy-to grasp video clip. Sims are very popular with academic teaching astronomers because they give students hands-on tools that are both challenging to work with and really fun to watch when they get it right. Here are a few:

Jim Stone's MHD sims of things like the way *galaxy bars* behave, how *black holes* grab and consume matter, and just why a huge, low-density *molecular cloud* cannot escape the fate of collapsing into the beautiful group of star clusters.

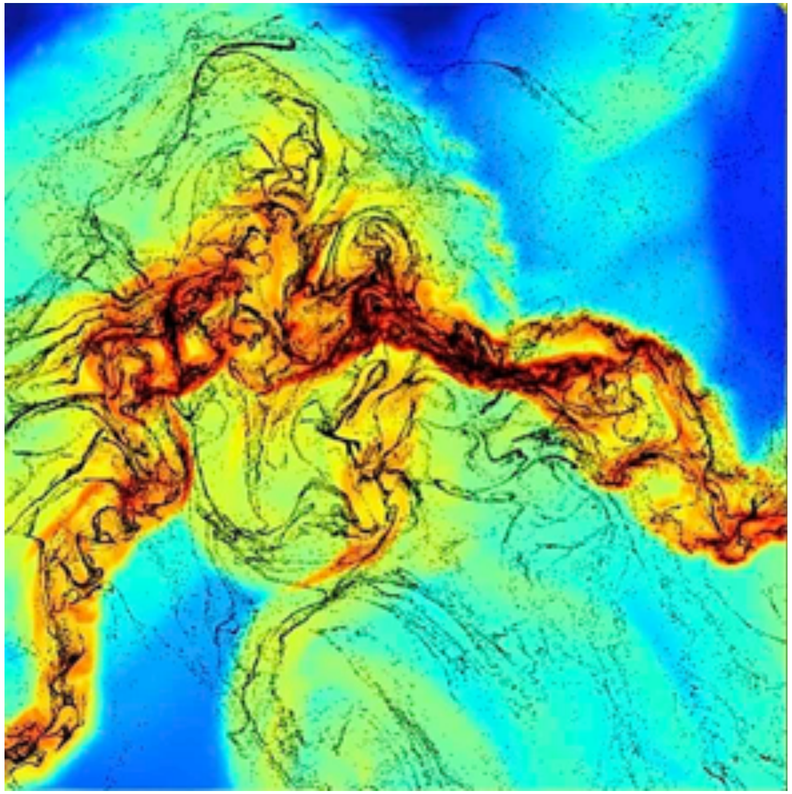


Fig 4-2 Turbulence generation in high-Mach gas flow, From Hopkins et al 2015, *The Fundamentally Different Dynamics of Dust and Gas in Molecular Clouds*.

Phil Hopkins' sims & animations cover a lot of territory. Here are a few:

Flying Through a Milky-Way Like Galaxy is just the ticket for amateurs who love hunting down galaxies. Have you ever wondered how any particular galaxy arrived at its present look? Barred spiral? Core-less flocculent spirals like M33? Grand-design spirals? Dwarfs? And what do the always-entertaining galaxy collisions (more accurately referred to as 'interactions' in the professional papers) look like from start to end? On this page Hopkins gives us a 10-item palette to choose from, all of them of a simulated galaxy that looks very much like our own.

Feedback Changes Everything simulates how individual galaxies form starting at redshift of 100 ($z = 100$) a time when the Universe was just a a few million years old. On this web page we can follow 11 different aspects of how a slightly denser region in the infant Universe becomes a galaxy like we see in the eyepiece today. These sims trace the evolution of dark matter and gas as they turn into stars. At first the stars light up the gas medium around them, then they alter it with their radiation by heating up the surrounding gas, which pushes on the gas and causes it to collapse into hugs, fiery regions like the Carina Nebula or Tarantula Nebula that wring out star clusters by the armload. And oh, those fireworks supernovae explosions that turn every galaxy thin disc into something resembling a water-jet display shooting up huge blobby sprays into the sky that then come back down as fine mist.

Galaxy Mergers with Feedback from Massive Stars is yet another 'Ooohh, aahhh' Hopkins effort. It is the most artistically beautiful because of the palette of colours chosen, which accurately mimic the Sloan u-g-r bands. These sims isolate out physics involved in four checkerboard panels: gas temperature, warm ionised gas (10^4 K), X-ray emitting gas ($> 10^6$ K) and gas surface density. That last one is important because when two expanding blobs of hot gas collide against each other the result is massive star formation on a more or less thin, flat plane. Now, what does the Milky Way disc looks like?

Matthew Bate's Star & Cluster Formation Animations are a godsend to anyone muddling through the rules & regulations (read: maths) of the way stars and star clusters assemble. There are over three dozen individual sims, grouped into seven main categories. Matthew's effort is as comprehensive a look at star and cluster mechanics as one can find — and not a single equation to throw ice water on the learning curve.

A good idea of Bates' overall content can be had *by viewing this sim*, which starts when a protocluster is still a dense ball of gas. Before long its first protostars light up and veer toward a very timid gravitational centre. A few stars form binaries. They hurl interlopers off at high speed, initiating the cluster's first stage of mass loss. (Watch how the binary tightens the interloper is ejected; the energy imparted to the interloper is subtracted from the binary's orbital energy.) Some stars erupt jets out of their poles (higher-mass protostar gas ejection), and in the end very massive O or B stars generate UV which heats up the natal gas to a glowing red (HII) and ejects it. The initiates the second round of cluster mass loss. In time all the mass losses add up and the cluster loses its binding energy and dissolves into the interstellar medium. Our Sun began life as a white dot in a real-life gas blob pretty much like this one.

All this between 136,606 and 228,402 years old. Show this to your kids when they wonder what you look at out there in the dark and watch their eyes get big and round.

Cosmology Sims

The universe has always excited imaginations. Few other topics have inspired as much creative modeling as portraying the entire universe throughout all time.

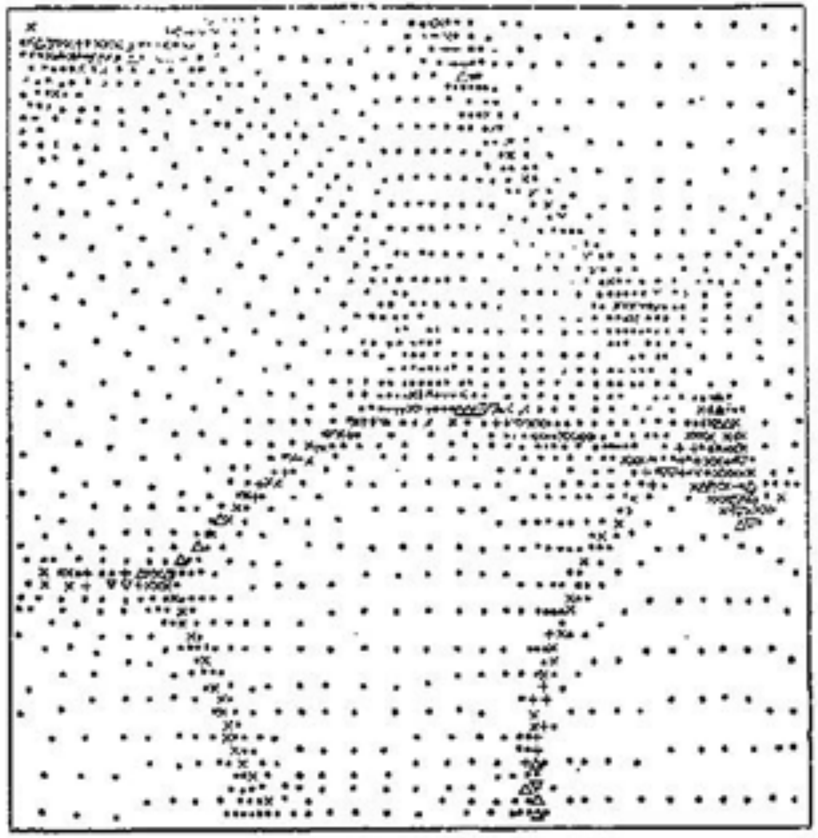
During the 1970s computer technology was widely applied to astronomy for the first time. Fifty years earlier General relativity and quantum physics suggested that the universe began as a single point at an inexpressibly hot temperature. In 1952 the astronomer Fred Hoyle derisively called it 'the Big Bang'. The name stuck but proof was lacking. Then the Penzias & Wilson 1965 detection of microwave photons from an epoch when the first atoms formed out of free electrons and protons put an observational foundation under the theory. At the same time, money (the flower girl at the marriage of theory and proof) made possible larger telescopes and more precise detectors. They soon leapt into space, delighting is ever after with splendours of the heavens we would see no other way. Along came affordable computers to deposit unheard of calculation speed and accuracy into astronomy departments all over the world. Every advance set the scene for the next advance. Next thing we knew they were in our cell phones.

From the outset astronomers hankered most of all to glimpse in some meaningful way the one entity they knew they could never actually see: dark matter.

Simulations filled space; galaxies soon followed

In 1973, Princeton University astronomers Jeremiah Ostriker and James Peebles devised numerical *N*-body simulations to study how galaxies work. *N*-sims as they were called had been known and used before, but memory limits and computer processing speeds yielded unrealistically coarse-grained models. Even Ostriker & Peebles had only 100^2 data points to represent objects in a plane. Today *N*-sims calculate tens of millions to billions of data points in 4D at megaparsec scales through the entire life of the Universe.

At the beginning globular and open clusters suited the *N*-sim technique best because gas mass could be ignored. Even though gas can be half or more of an embedded cluster's total mass, it is diffuse and subject to local turbulent shocks and long-range magnetic forces; for the purposes of a sim, stars are concentrated and little affected by these. Ostriker & Peebles used Newton's Universal Gravitational Law

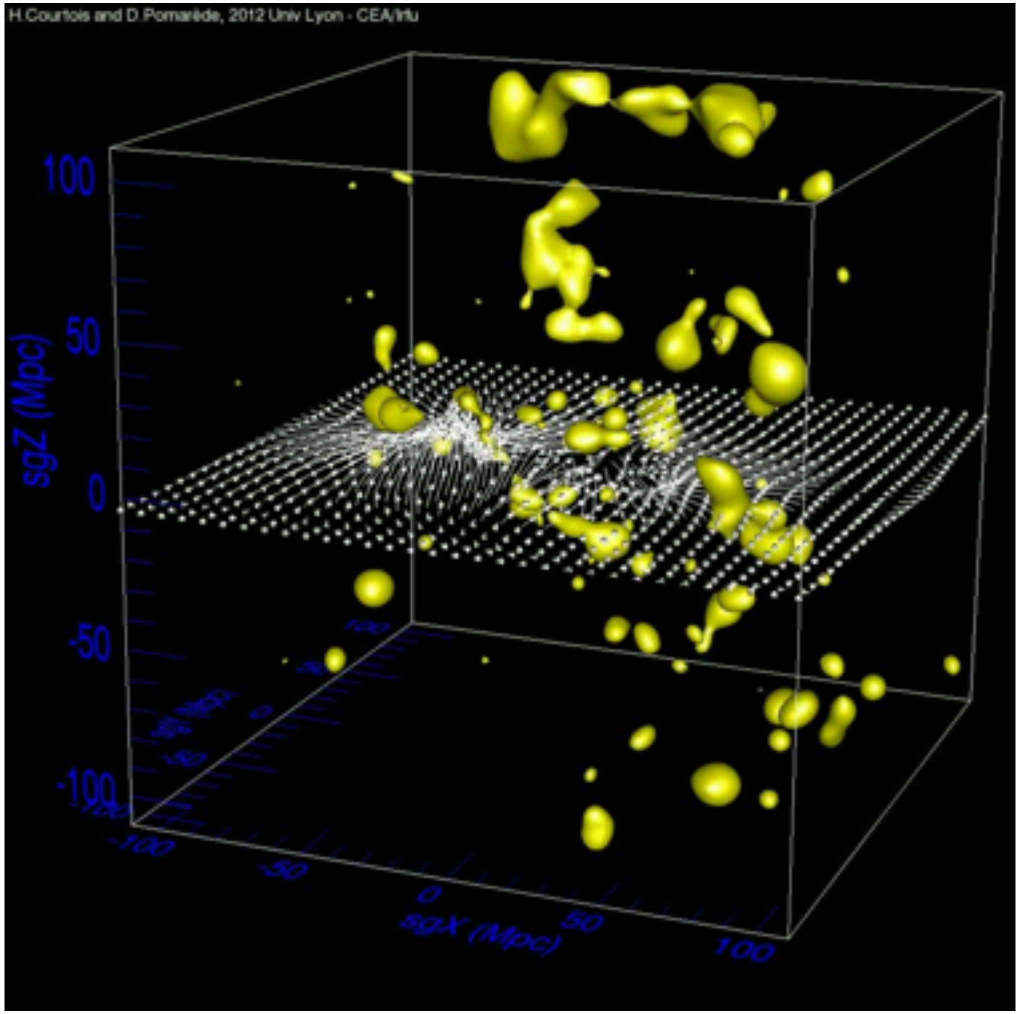


The first simulation of structure formation was made in mid-1970s by Yakov Zel'dovich et al. in the Institute of Applied Mathematics in Moscow using the largest available computer at the time. The sim began with a data square of 100 particles on a side, each particle standing for 10^{12} $M_{\odot}$ gas mass, which was calculated to be the average mass of a 'halo' in the era between the end of Inflation and the era of Recombination (z = >> 1100). As the original 1977 simulation ran, an evenly distributed grid of high-density filamentary structures evolved as low-density regions emptied into voids. At the time this was interpreted as a cellular structure. Over the next 10 years it evolved into the filament-and-clump Cosmic Web familiar to us today. *Source:* *Einasto 2009*.

to compute how far gravitational force would vector sets of mass points across given increments of time. By iterating each set of calculations many times to smooth out runtime errors and scatter, Ostriker and Peebles discovered that a galaxy's self-gravity proportionated more mass points (stars), toward the centre while gas masses tended to disperse out towards the edges. Their sim implied that star masses have very tiny, dense cross-sections while gas masses have very large, weak cross sections. Unfortunately, the N-body results didn't match observed galaxies. Real stars and gas in space do not fractionate this way. In a spiral galaxy like our own, gas blobs and stars rotate in only lightly perturbed circles around the galaxy's centre of mass. Using the known mass of our galaxy (1.8–2.1 x 10^9 $M_{\odot}$) and its known size (4 x 10^{20} metres dia.), the mass point representing the Sun was calculated to orbit at about 200 km/sec, or ±50 million years to orbit the galaxy. The actual values are 247 km/sec and 220 Myr. The more variables the pair introduced, the more scattered their results.

Then the team heard about *Vera Rubin & Kent Ford's 1970* analyses of the Andromeda Galaxy's rotation curves. They introduced a electromagnetically inert but gravitationally active 'stuff' three to ten times as massive as the sim's stellar gas. The results looked like real galaxies. *N*-sims added numerical proof to the existing observational demonstration that dark matter was necessary to account for the shapes and mass distributions of real galaxies in real space.

You can read fascinating accounts of this foundation-stone era with Jim Peebles' 2017 account of events he participated in during the great era of cosmic-web discovery *here*, Jaan Einasto's 2009 account is *here*, and Zel'dovich's *1970 first theoretical paper is here*. The most thorough rendering of the complex physics involved when the Cosmic Web was



Still image cut from the CLUES full 64 MB video *Tomography of the 3D velocity field*. The image slice shows an isodense plane (the particles are spread evenly and all the same mass) as it glides through calculated gravity fields surrounding galaxy superclusters (yellow blobs). The planes are warped byintense gravitational potentials, but by the end of the slice that they have returned to their isodense state. The sim can be read in several ways because the contours are idealised physical states that might be actual particles, a shock wave, magnetic potential, or any specific electromagnetic photon band, e.g., radio. Source: CLUES team Hélène Courtois & Daniel Pomarède. You can bookmark this as a downloadable clip using *Tully08_UG_040611_160_R60_div_scanvectors-small-640.avi*.

reconfigured to include Dark Matter theory in *Johan Hidding et al. 2013*.

CLUES

The CLUES project depicts cosmological behaviour using constrained simulations of the local universe to prove/disprove whether the visible mass in the universe is an accurate reflection of the distribution of dark matter mass. Using numerical simulations to study galaxies and the large scale structure of the Cosmic Web was an effective and easy-to-comprehend way to understand how the filament-and-void Cosmic Web that has been actually observed grew out of the initial mass density and energy density conditions in the infant Universe.

N-body sims begin to lose their appeal when structures become gigantic and time scales vast. To give them credit, *N*-sims and other numerical methods like them have been the driving force behind much of the theoretical progress in the evolutionary behaviour of astronomical bodies. Still, they have their drawbacks. Any simulation technique has to balance achieving a meaningful spatial resolution and accurately representing the physical behaviour that goes on in it. This boils down to: the more data points you use, the more realistic your visualisation. (This assumes that the computer algorithms are right, of course — we never seem to hear about the awful ones.) The bugbear, though, is the cost of computer time and the number of people required to programme, run, and interpret the results.

The CLUES project was initiated to find workarounds. Their idea was to constrain the initial conditions of their simulations using actual observations of the mass/energy distribution in the nearby universe. Unsurprisingly, their approach is called 'constrained simulation' (CS) and we come across that term everywhere in the world of cosmology simming. We have quite accurate data for the properties and behaviour of the local Universe out to 100 Mpc and to at least $z = 1$ (6.78 Gyr). Things get fuzzy beyond these, but that is exactly the scale of the Universe that cosmologists want to portray with a high degree of confidence. Constrained simulations are designed to *reproduce large scale structure using local scale properties*. [The '*GA*' in the image means 'Great Attractor'.] CS uses different particle box sizes and resolutions, within which they apply parameters like (a) gravity only, (b) gravity including gas physics and star formation, (c) gas temperature, (d) gas density, (e) metallicity, (f) baryonic mass, and (g) dark matter mass. The term 'local' means the neighbourhood within a few tens of megaparsec around the Milky Way. In effect CS de-randomises arbitrary parameters. Get it right locally and you are likely to get it nearly right everywhere else. Nothing's perfect whether near or far, but at least you can smooth the wrinkles on what's far.

Anyone from grammar school student to varsity graduate, can instantly comprehend the way the universe works without having to go through ten years of life acquiring a Ph.D. The CLUES poster child is the 17-minute *Cosmography of the Local Universe* by the CLUES directors Hélène Courtois, Daniel Pomarède, R. Brent Tully, Yehuda Hoffman, and Denis Courtois. Read the *original descriptive paper here*.

While the *Cosmography of the Local Universe* is by far the best-known and most-watched CLUES project, their website has a great many other computer sims of the larger-scale side of cosmology. Check out the *Images and Movies* section of their website.

Fun time at the keyboard You can DIY your own CLUES-like sims using *their very own website here*. Be sure to check out Gadget 2 and 3. You can also create your own realistic cosmology videos using Arman Khalatyan's *PMViewer Rendering Framework* using a mouse click

ILLUSTRIS

There are two ways to crunch the bogglingly big numerical calculations that make up cosmology sims. One is to use the entire processing capability of a massive mainframe computer for several months to produce a single 10-minute video clip. Organisations that need this much time write their algorithms so their project fits into the holes of spare unallocated time on the computer. That means thousands of additional lines of code, or more realistically, dozens of coders being paid by the hour or line. The Max Planck Institute in Heidelberg and the Kavli Institute in Beijing take this approach because they use giant computers dedicated solely to their processing.

It can be done cheaper if there are a great many people who want and know how to do it. Hence massive number-crunching projects are mostly undertaken by university computer departments that have an overabundance of master's degree students eager to prove their skills.

The other way is massive parallel processing wherein hundreds of desktop PC computers are harnessed together as a team. This is a lot cheaper but takes longer if you apply the same multi-step, multi-line algorithms as the mainframe users do. Boggling elaborations are presented when using hundreds of home computers all over the world while the owners snooze or eat.

The Germany-based ILLUSTRIS Project uses a mix of both methods. Their method therefore requires the most sophisticated algorithm coding imaginable. *GADGET 2* does best. ILLUSTRIS produces the best astronomical eye candy the sim world has produced so far. To start with, these folks think B-I-G. Their data cubes run from 10 megaparsec to over 1.2 gigaparsec on each side and hopscotch across eonic-scale time frames that compress 10 or 20 million years into one second. That's how the ILLUSTRIS *crême-de-la-crême* videos that depict the progress of the Universe from $z = 1100$ (when the Universe first became transparent) to you and me sitting front of a glowing screen. See *1*, *2*, *3*. The vids are very high resolution, packing hundreds of massive parallel-processing computer hours into events like thousands of supernovae going off all over the Universe across 100 million years. Show this one to you wife and kids the next they ask what you look at through that long white tube with the glass thingie on the end that keeps getting foggy. This cube is only 10 megaparsec on a side in a Universe that would be 46 gigaparsec on a side.

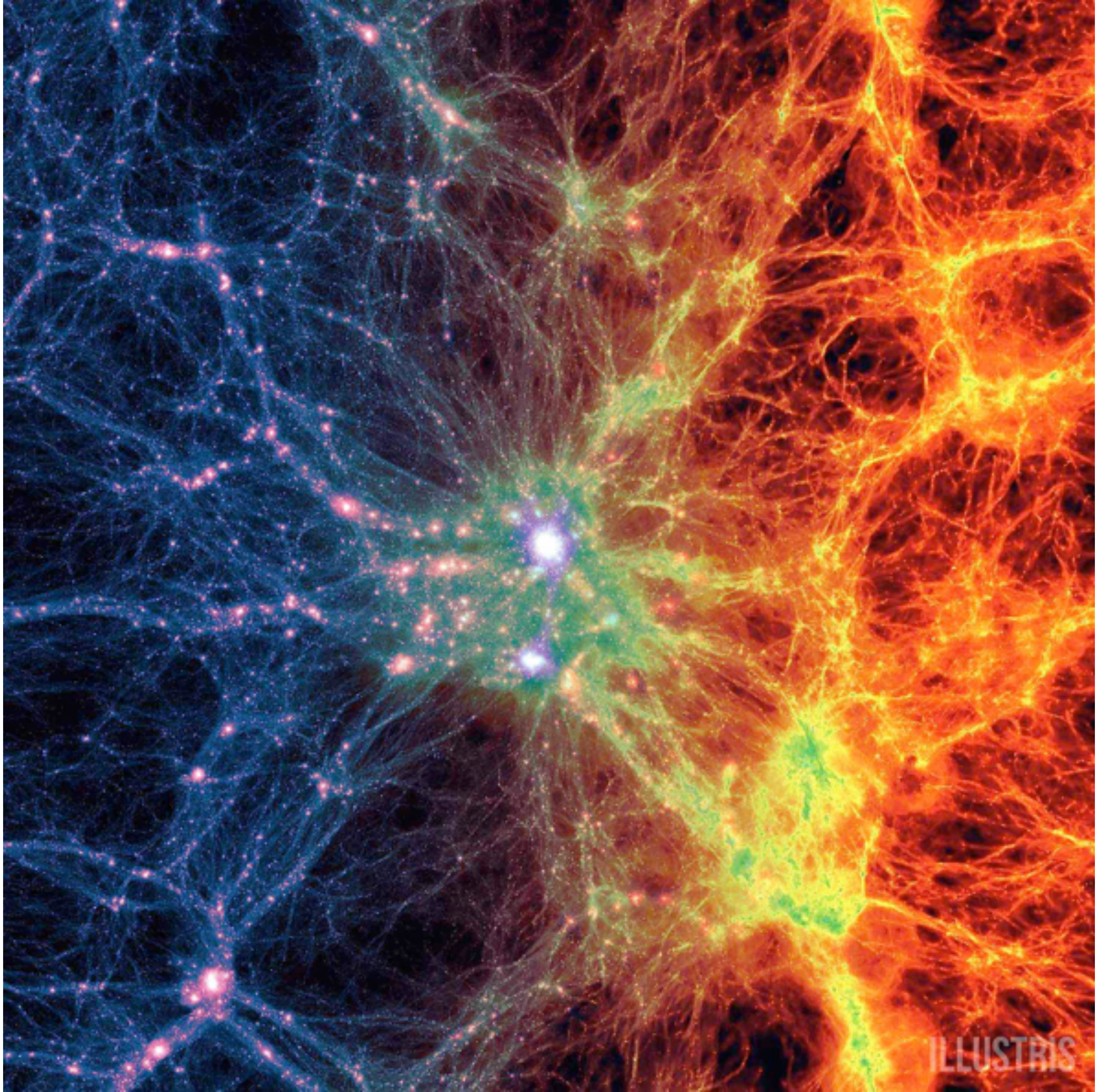
We have to be careful when showing sims to non-astronomers. Illustris has the *most startling sim* most of us will ever see. Show this to the proverbial person on the street. Explain beforehand that it shows what happens in a volume of space 100 Mpc on each side as it evolves through 495 million years. After the initial moment of dumbfounded awe, the question you will likely hear is, 'Wow, does this mean the Universe is *thinking*?'

Indeed, the sim really does look like electron transport along neural networks. In most people's perception this is what the inside of the brain would look like on the scale of biological nerve networks.

In actual fact this sim is a 3D tomographic MHD fly-through of cosmic filament/superclustering with all three tomographic slices moving at once. Slow it down to a slice-by-slice level and *this is what you see*.

When viewing these any the many other sims that will be reviewed in future *Nightfall* issues, the most important question of all is, 'What can I learn from these?'

= Douglas Bullis



Large scale projection through the Illustris volume at z=0, centred on the most massive cluster, 15 Mpc/h deep. Shows dark matter density (left) transitioning to gas density (right).

Sagittarius Dwarf Irregular Galaxy <http://www.eso.org/public/images/potw1805a/>

The Pişmiş Catalogue

By Susan Young

Exquisite Pişmiş 24 lying in emission nebula NGC 6357.
Image credit Hubble/ESA

Open clusters are exquisitely beautiful. From the lovely daintiness of the small clusters to those blazing with brilliance, they display immense beauty and symmetry… the gorgeous colours, the range of magnitudes, the winding loops and chains of stars, the dark voids, whole fields scattered with diamond dust, the delicate glow of unresolved starlight… all so different, all so beautiful.

The twenty four Pişmiş open clusters don't blaze. A few of them are exquisitely bright and delicate, others appear as tiny glints of stars mingled with a faint hazy glow of unresolved starlight, and yet others appear as little more than a faint and tantalizing mistiness. But they certainly make a delightful little observing project! They were discovered by Paris Pişmiş, a remarkable astronomer who played a significant role in enriching the field of astronomy.

Paris Pişmiş (1911-1999)

Marie Paris Pişmiş de Recilas (1911-1999) was born on January 30, 1911 in Istanbul, the daughter of an Armenian family who were of great prestige in their community. She completed her high school studies at Üsküdar American Academy.

She was one of the first women to attend Istanbul University. She enrolled in the Faculty of Sciences and earned a PhD in Mathematics in 1937. Her supervisors were Professors R. Von Mises and Erwin Finley-Freundlich (she served as an interpreter and research assistant to Freundlich). As a student, Pişmiş worked at the Istanbul University Observatory.

In 1938 Pişmiş travelled to the United States to become an assistant astronomer at Harvard College Observatory for a year. However, with the outbreak of World War II it did not seem advisable for her to return to Turkey so she stayed on at Harvard until 1942 when she married Félix Recillas, a Mexican astronomy student, and they moved to Mexico to join the recently founded Observatorio Astrofísico de Tonantzintla in Puebla. Pişmiş worked there until 1946. In 1948, she moved to Mexico City where she joined the Observatorio Astronómico Nacional at Tacubaya, which was part of the Universidad Nacional Autónoma de México (UNAM). For more than 50 years, she worked at UNAM where she became Astronomer Emerita in what is now known as the Instituto de Astronomía.

Pişmiş' primary interest was galactic structure. She carried out some of the first photometric observations of young stellar clusters and discovered the globular cluster and 20 open clusters that appear on her 1959 catalogue, as well as another open cluster she co-discovered (Pişmiş-Moreno 1). She also studied the effects of interstellar absorption in stellar associations on the observed stellar distribution. She sought to explain the origin and development of the spiral structure of galaxies and to discover a reason for the waves of their rotation curves, based on different stellar populations. In 1972, she introduced Fabry-Perot interferometry to Mexico to study the velocity field of galactic emission nebulae.

Janet Akyüz Mattei, Dorrit Hoffleit, and Paris Pişmiş (top to bottom), Mexico City, 1993. Image credit AAVSO Archives, Janet Mattei Collection

During her lifetime she visited over 20 nations, giving astronomical lectures in any of six languages – Turkish, English, French, German, Italian and Spanish. In Mexico she supervised at least half a dozen PhD theses by graduate students at UNAM. She was a tremendous role model for women astronomers – of the approximately 80 astronomers at UNAM over the years, 25% were women. Dorrit Hoffleit (1907-2007) wrote, "She is the one person most influential in establishing Mexico's importance in astronomical education and research".

Pişmiş published her memoirs in 1998 under the title, *Reminiscences in the Life of Paris Pişmiş: a Woman Astronomer* (but alas, the book is long out of print and seems unobtainable; what a great read it would be). She died in Mexico City on 1 August, 1999.

Proof of her great commitment to her field can be seen in our southern skies… using the existing Schmidt plates of the Tonantzintla Observatory, she discovered 24 open clusters and 2 globular clusters, and published her *Nuevos Cumulos Estelares en Regiones del Sur* (New Southern Star Clusters) catalogue in 1959.

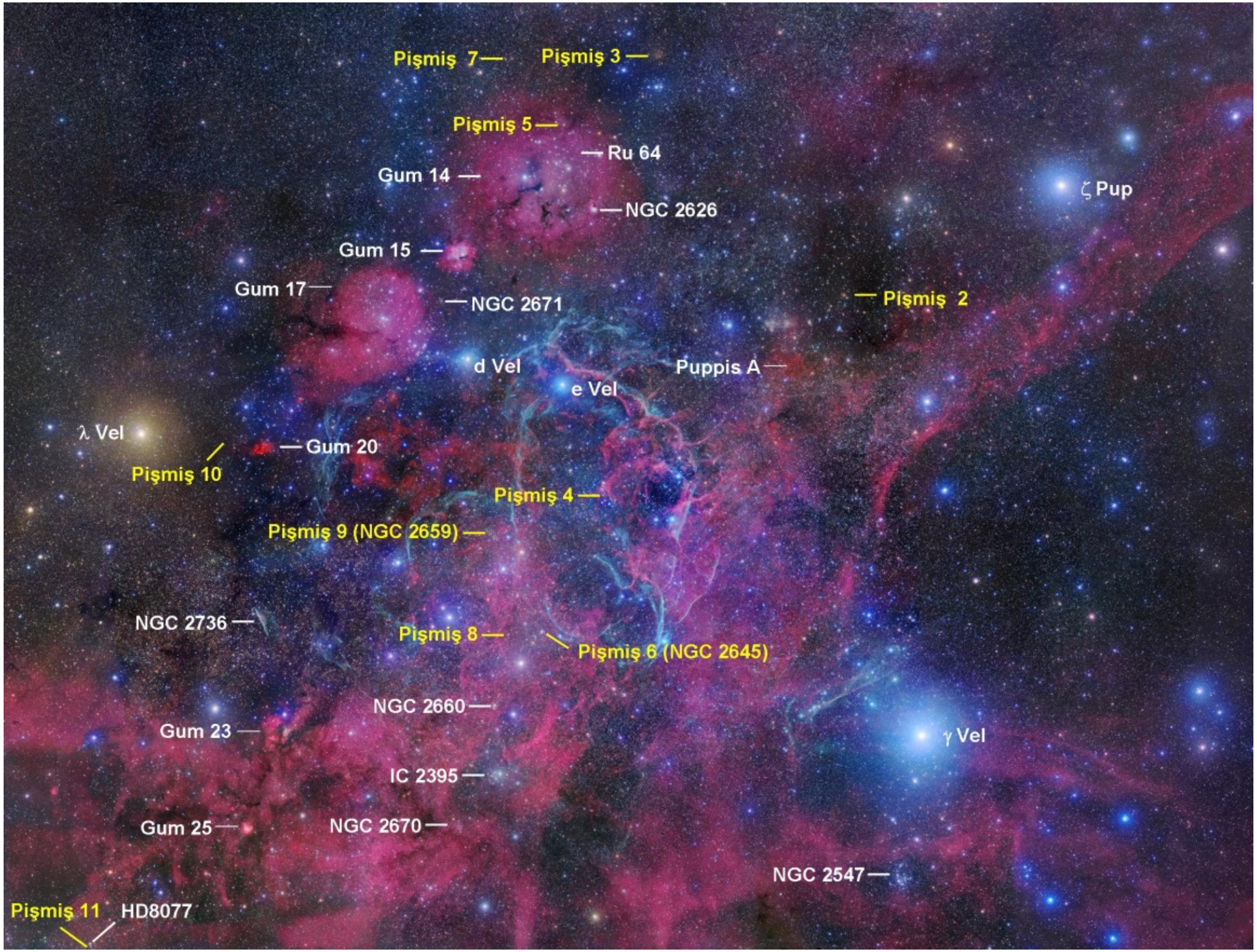
Of the 24 open clusters, four had already been discovered: Pişmiş 1 (NGC 2568) was discovered by E.E. Barnard in 1881; John Herschel discovered Pişmiş 6 (NGC 2645) in 1834 and Pişmiş 9 (NGC 2659) in 1835; and Pişmiş 18 (IC 4291) was discovered by Robert Innes in 1901.

The globular cluster Tonantzintla 1 (Pişmiş 25) is NGC 6380, and had been discovered by John Herschel in 1834, but Tonantzintla 2 (Pişmiş 26) was a new discovery.

Tonantzintla 2 (Pişmiş 26). Image credit 2MASS

Some time ago, when I was exploring the vast and spectacular tendrils of the Vela SNR, small slews of the telescope brought a treasure trove of other objects into view, so for the blog I wrote, I annotated an ESO image of the region… and was dumbfounded to discover that ten Pişmiş open clusters could be seen in the image, with another half dozen just around the corner, so to speak.

On the following page is the image with the ten Pişmiş open clusters annotated on it.



The stupendous Vela SNR region, showcasing 10 Pişmiş open clusters.

I used my 16" f4/5 Dobs at 200x to observe the small and delicate Pişmiş clusters. In the data for each cluster, I have included Paris Pişmiş' notes from her 1959 catalogue, as I found it very interesting to compare her notes with what I saw in the eyepiece.

Pişmiş 1 = NGC 2568 (Puppis)

$08^h18^m18.0^s$ -37°06'00"

Mag 10.7   Dim 3'   Number of stars 30

Note: The bright stars seem aligned like chains

A small, faint cluster consisting of about a dozen mag 12.5 and fainter stars. "The bright stars seem aligned like chains" and indeed they do… the brighter stars forming a curving NS arc, and a less obvious, fractured-looking NW-SE chain of fainter stars lie to its west.

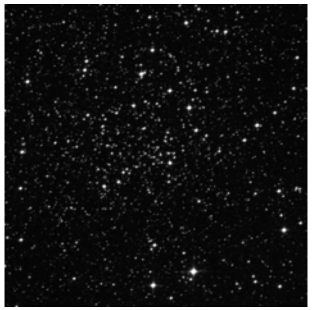
Pişmiş 2 (Puppis)

$08^h17^m57.8^s$ -41°40'12"

Mag 10.7   Dim 4.0'   Number of stars 100

Note: Very beautiful object, symmetrical

Albeit it faint and small, this cluster is very beautiful in its symmetry… it appears as a faint round patch of soft misty unresolved starlight with a mag 12.5 star its western edge, and with averted vision, the tiny glints of a couple of faint stars dance in and out of view.



Pişmiş 3 (Vela)

$08^h31^m15.6^s$ -38°39'28.8"

Mag 10.7   Dim 6.0'   Number of stars 50

Note: Bright stars in the shape of a crown

I can't see the shape of a crown; the cluster appears as a faint scraggy-shaped haze of misty pearl-coloured unresolved starlight with a mag 12 star lying the western edge. With averted vision, tiny faint stars glint in and out of view.

Pişmiş 4 (Vela)

$08^h34^m40.8^s$ -44°29'42.0"

Mag 9   Dim 25'   Number of stars 45

Note: The nebula appears in the lists of Gum (16) and Cederblad (106g); elongated as the cluster

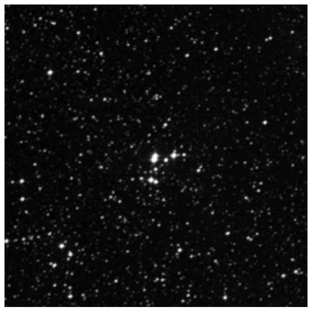
This is a gorgeous scattering of a few beautiful bright mag 8-11 stars that lie in a elongated N-S direction with a few fainter stars scattered around. With the OIII filter and averted vision, I can make out a very faint, very fragmented streak of very pale nebulosity running almost parallel to the cluster on its western side. (An OIII filter is a must for observing the SNR tendrils.)

Pişmiş 5 (Vela)

$08^h37^m39.8^s$ -39°34'48.0"

Mag 9.9 Dim 2.0'   Number of stars 10

This very attractive little cluster lies on the northern shores of the very attractive loose sprawl of stars of mixed magnitude that make up the Ruprecht 64 open cluster. It has ten stars displaying attractive patterns: there is a close pair in the centre of the cluster, another brighter close pair to the south, a tiny triangle of faint stars on the north western edge, and a tiny arc of three faint stars on the eastern edge.



Pişmiş 6 = NGC 2645 (Vela)

$08^h39^m02.8^s$ -46°13'58.8"

Mag 9.2   Dim 1.5'   Number of stars 15

Note: Two pairs of doubles, including the brightest star

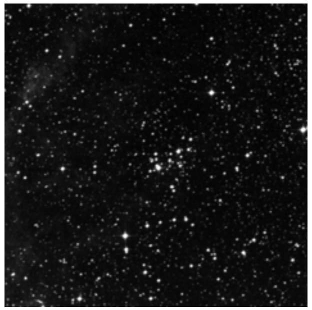
A beautiful and bright little cluster! It has around a dozen stars compactly packed into a stunning bright knot. The four brightest stars form a striking right-angled triangle and include the "two pairs of doubles, including the brightest star" – the right angle itself is an eye-catching pair of close bright white mag 9 stars, and the other double lies to its south, and is a slightly less tight white mag 9.4 star with a white 10.6 companion. The fourth star, a mag 9 star lies west of the right angle double. The other fainter stars lie haphazardly scattered around these four bright white stars. Lovely!

Pişmiş 7 (Vela)

$08^h41^m12.0^s$ -38°42'25.2"

Mag 7.3   Dim 3.0'   Number of stars 35

This cluster appears as an extremely small, extremely faint dusting of misty unresolved starlight, with a very faint star on its southern edge. It just barely stands out as a cluster among the rich field of stars.



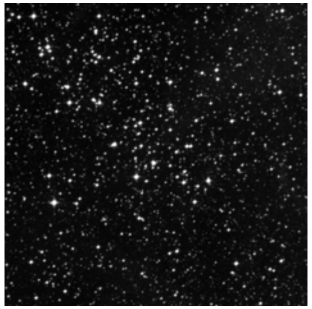
Pişmiş 8 (Vela)

$08^h41^m39.6^s$ -46°16'01.2"

Mag 9.5   Dim 3.0'   Number of stars 25

Note: Is in a region of high absorption

This small cluster appears as a small, soft pearly glow of unresolved starlight with the glints of a few faint stars resolved across it. A fuzzy-looking mag 11 star lies at the south eastern edge of the cluster. With the OIII filter, a very thin, and very faint arc of nebulosity lies to the east, its open side to the west wherein lies this cute little cluster.



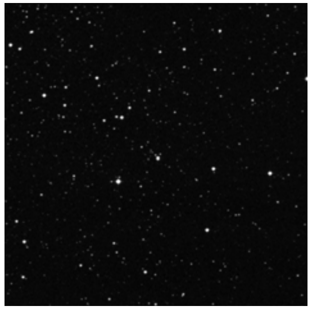
Pişmiş 9 = NGC 2659 (Vela)

$08^h42^m34^s$ -44°52'48.0"

Mag 10   Dim 3.3' x 2.2'   Number of stars -

Note: It includes −44° 4728 ; open cluster

A pretty little cluster. A bright, compact group with just over a dozen approx. mag 12 stars sprinkled across a lovely gathering of fainter stars in an oblong shape, elongated NE-SW. The stars appear to be more concentrated in the SW end of the oblong. With the OIII filter there is a very faint blurry patch of nebulosity to the west and a nice, albeit also very faint, thin roughly E-W streak of nebulosity to the SE of the cluster.



Pişmiş 10 (Vela)

$09^h02^m38.1^s$ -43°38'09.6"

Mag 10   Dim 1.5' x 3.5' Number of stars - 5 Neb

Note: It includes 48° 4354

I searched long and hard for this cluster but couldn't make out anything that even began to resemble this very sparse random-looking scatter of 5 dim stars. And no sign of any nebulosity.

Pişmiş 11 (Vela)

$09^h15^m52.9^s$ -50°01'00"

Mag -   Dim 2.5'   Number of stars - 20

A lovely little cluster! Three mag 12-13 stars in a tiny arc and embedded in a mist of small stars and unresolved starlight, appearing to dangle from the gorgeous blue-white mag 9 supergiant HD8077 like a piece of delicate filigree dangling from a diamond.

Pişmiş 12 (Vela)

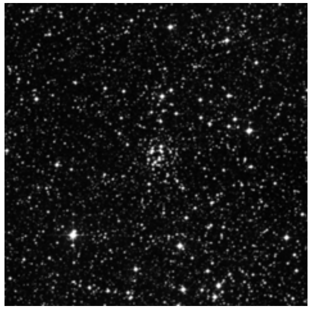
$09^h20^m00.3^s$ -45°06'54.2"

Mag 9.7   Dim 5.0'   Number of stars 20

Note: Circular symmetry, beautiful object

This cluster doesn't have a circular symmetry to my eye, although it is beautiful in an understated way. It appears as a scraggly, irregular-shaped cluster with attractive orangey mag 6.7 HD 80777 as its SE edge, a nice triangle formed by three mag 12 stars at its northern end, and another mag 12 star at its western edge. The rest of the stars are fainter, most of them lost in the soft background glow of unresolved starlight, except for a little grouping of mag 13 and 14 stars that lie near the eastern edge of the cluster.

Pişmiş 13 (in NGC 2866, Vela)



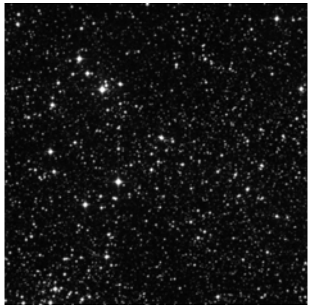
$09^h22^m06.9^s$ -51°06'07.2"

Mag 10.2   Dim 2.0'   Number of stars 30

Note: Five bright stars inside 1'

I confess that I have always found it difficult to define exactly what bright scattered stars comprise the open cluster NGC 2866 as the field itself is rich in stars of mixed magnitudes. But there is no doubting the cluster's little heart… very pretty little Pişmiş 13. It contains over a dozen mag 12 and fainter stars against a beautiful irregularly round patch of unresolved starlight. It has two nice pairings – a close double at the north of the cluster, and another close double on the east side of the cluster.

Pişmiş 14 (Vela)



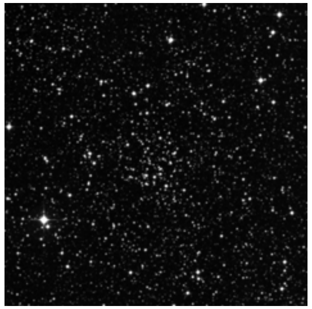
$09^h29^m52.8^s$ -52°46'48.0"

Mag -   Dim 1.5'   Number of stars 12

Note: At the edge of the plate; on the dark background one suspects the existence of the weakest members

I couldn't pinpoint this cluster, although there were three definite maybes… never a good thing! But it certainly is gorgeous stellar real estate to be scratching around in… chock-a-block with stars… the three small "maybe" gatherings of faint stars lying among a number of lovely bright stars that lay scattered around.

Pişmiş 15 (Vela)



$09^h34^m45.1^s$ -48°01'48.0"

Mag -   Dim 5.0'   Number of stars 35

Note: Similar to number 12; circular symmetry

Unlike number 12, where I couldn't see the circular symmetry, this faint glow of starlight did appear round – a misty sheen of unresolved starlight against which a few tiny stars glinted in and out of view.

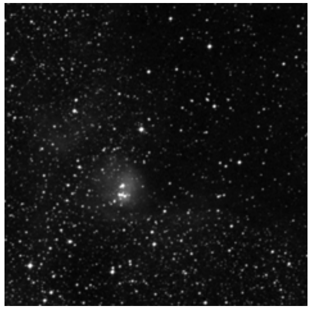
Pişmiş 16 (Vela)

$09^h51^m16.8^s$ -53°10'01.2"

Mag 8.0   Dim 2.0'   Number of stars 12

Note: They are members −52° 3412 and −52° 3413 (double of comparable brightness)

Another exquisitely small open cluster – albeit faint, it has the most delicate teardrop shape with the tip facing SW. Its four brightest stars form a beautiful little chain along the teardrop's southern edge, with the fainter members filling out the teardrop with a beautiful mistiness of unresolved starlight against which a couple of stars pop in and out of view with averted vision.



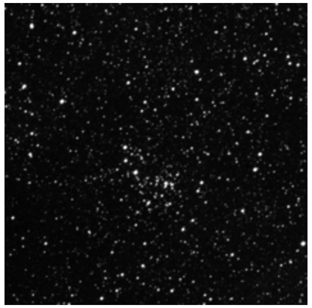
Pişmiş 17 = NGC 3503 (Carina)

$11^h01^m04.0^s$ -59°49'04.8"

Mag 9.4   Dim 0.6'   Number of stars -

Note: Quadruple star in nebulosity plus five faint stars; is the center of arcs that extend up 15'. Similar to NGC 2467

This is a delightful little cluster – lying in a rich field of stars, it stands out well…. a delicate triangle of stars – the base of the triangle formed by a delicate E-W trio of stars, with the apex north of them; itself a nice mag 10.5 star with a very faint close companion. The cluster itself lies in a faint haze of nebulosity that has no defined edges and simply dissolves away into the star-rich background. No particular contrast gain with the UHC filter. (I looked at NGC 2467 in Puppis, a large bright nebulosity surrounding a mag 7.8. In a way Pişmiş 17 looked a little like an exceedingly small, distant and faint NGC 2467 at low magnification.)



Pişmiş 18 = IC 4291 (Centaurus)

$13^h36^m55.9^s$ -62°03'54.0"

Mag 9.7   Dim 4.0'   Number of stars 35

Note: Six stars brighter than 10.5m to 12m; the brightness of the members gradually declines

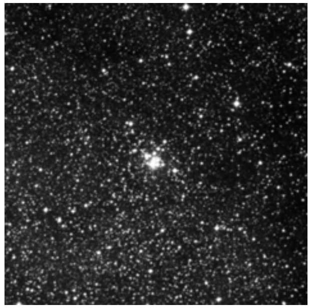
A pretty little cluster, a triangular shaped cloud of starlight with its apex at the NE and marked by a mag 10.9 star. A handful of mag 11-12 stars are scattered across the haze of unresolved starlight, and there is a pronounced dark patch on the cluster's NNW side. The stars appear to be more concentrated in the SW base of the triangular shape.

Pişmiş 19 (Centaurus)

$14^h30^m36.0^s$ -60°53'06.0"

Mag -   Dim 3.0'   Number of stars 60

This is an enchanting little cluster, not for its appearance, but its location… it lies between alpha and beta Centauri. Gorgeous alpha Centauri lies around 1.1′ to its ESE, and the beautiful, large, fairly rich cluster NGC 5617 lies to its NW. A noticeable triangular asterism points from NGC 5617 at Pişmiş 19… indeed, this small faint cloud of misty starlight appears to dangle to the SE from the star at the apex of the triangle, a mag 9 star with a very close mag 10.5 star to its south.



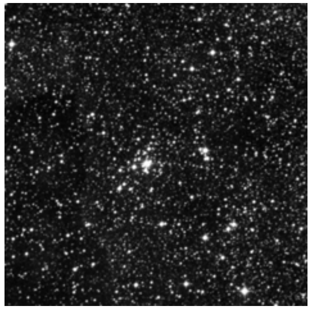
Pişmiş 20 (Circinus)

$15^h15^m23.0^s$ -59°04'01.2"

Mag 7.8   Dim 4.5'   Number of stars 12

Note: The five brightest stars, inside 0.6'

This little cluster reminds me that not everything has to be blazingly beautiful to be beautiful… this small and delicate cluster is utterly gorgeous! Four mag 8.2 – 11 stars are arranged in a tight little box-shape towards the middle with rest of the fainter stars spilling out from the boxy middle in a couple of short but gorgeous starry rays, the longest of which points to the northwest. A lovely rich starry background.



Pişmiş 21 (Circinus)

$15^h16^m44.4^s$ -59°39'18.0"

Mag -   Dim 2.0'   Number of stars -

Note: At the edge of the plate

This tiny little cluster appears as a small, bright, tight little knot of stars, set against a very small faint cloud of mistily unresolved starlight, with one small, faint star glinting to the east.

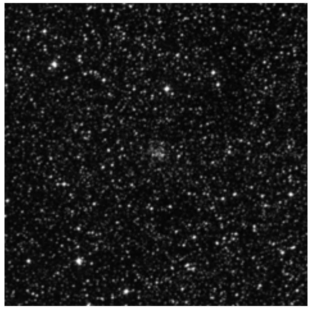
Pişmiş 22 (Norma)

$16^{h}14^{m}13.2^{s}$ -51°51'54.0"

Mag - Dim 4.0' Number of stars 30

Note: Seven of the brightest stars in a suite aligned in declination. Multiple star?

A very unusual cluster! The "seven brightest stars in a suite aligned in declination"… I can see four mag 12-13 in a row, along with one more to the east towards the northern end of the row. The rest of the cluster appears to be lost in a faint circular glow of unresolved starlight around the 'suite'. The attractive orangey star, HD 145542, lies to the SSW.



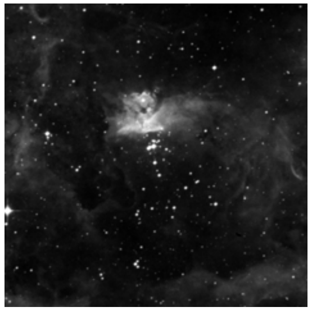
Pişmiş 23 (Norma)

$16^{h}23^{m}58.0^{s}$ -48°53'31.2"

Mag - Dim 1.0' Number of stars 15

Note: Very faint

Alas, "very faint" translated to "not visible" in my telescope. But oh my, a stunningly beautiful field in which to search for a very faint cluster!



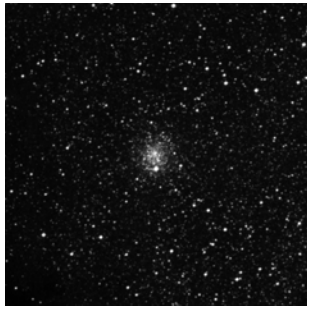
Pişmiş 24 (Scorpius)

$17^{h}24^{m}43.0^{s}$ -34°12'23.0"

Mag 9.6 Dim 2.0' Number of stars 15

Note: Inside a condensation of the big nebula around NGC 6557

It appears that in her notes, Paris did what we have all done… stuck a wrong digit into an NGC designation: NGC 6557 is a galaxy in Octans whereas her striking little cluster lies within NGC 6357 in Scorpius. Without a filter, the cluster is beautiful; a very pretty double star (mag 11-12) double star; the star to the east appearing fuzzy, and with a few very faint stars popping in and out of view to the north of the double. A very faint mist of nebulosity can be seen to the north of the cluster – and it responds significantly to the OIII filter, appearing as a very nice WSW-ENE elongation of nebulosity that is quite a bit brighter in the middle, due north of the double.



Pişmiş 25 = Tonantzintla 1 = NGC 6380 (Scorpius)

$17^{h}34^{m}28.0^{s}$ -39°04'09"

Mag 11.5 B Vm 17.0 HB Vm 19.5 Diam 3.6'*

This is a very tough globular! Lying in a lovely star-rich field, it is very, very faint, very small, has a very low surface brightness, is very diffuse, has no central concentration, and to boot its feeble glow is swallowed up the glare from a mag 10 star on its SSW edge, which makes it even more difficult to see. I could only pick it up with averted vision, and even then it tended to disappear and reappear.

Pişmiş 26 = Tonantzintla 2 (Scorpius)

$17^{h}36^{m}10.5^{s}$ -38°33'12"

Mag 12.2 B Vm - HB Vm 18.2 Diam 2.2'*

This globular is exceedingly tough! I only picked it up with averted vision after a long, concentrated look, and even then I couldn't hold it; the tiny, incredibly faint glow, so diffuse it was almost transparent, flickered in and out of view in a maddening way – more out of view than in.

UV erosion of gas/dust clumps in NGC 3372, South Pillar, Carina Nebula

Seeing the Dark

Coal Sack Nebula by Byron Bay Observatory, Australia.

Holes in the Heavens

One night in 1784 the usually reserved William Herschel exclaimed to his sister Caroline recording his observations on the ground below, '*Hier ist wahrhaftig ein Loch im Himmel!*', or 'Here is truly a hole in the heavens!'. She dutifully recorded it, even including the exclamation mark.

Herschel's telescope pointed towards the Ophiuchus region. He had glimpsed one of the dark nebulae in the Ophiuchus Nebular Complex. He reported the discovery the following year *(Philosophical Transactions Series I* 75:2135, 1785). For the next century until astrophotography arrived in the hands of E. E. Barnard, astronomers were undecided whether these dark objects were true voids or regions that simply lacked stars (after all, that's what the great Herschel himself said). Or perhaps they might by nebulae just like bright ones except that they didn't shine.

When Edward Emerson Barnard fitted the focal plane of his telescope with glass plates covered with a thin silver-halide emulsion, he found that the dark patches were suffused with significant density gradients of emission. They ranged from light grey to truly black. They exhibited a potpourri of clumpy and filamentary morphologies (shapes). They could absorb emission from behind them while not emitting any of their own. Barnard published the best of the plates in the first systematic dark-cloud photographic survey, *On the Dark Markings of the Sky** (Barnard E.E., *Astrophysical Journal* 49:1-24, 1919. Eight years later the plates were published in book form, *Catalogue of 349 Dark Objects in the Sky*, Univ. of Chicago Press, 1927). Today that book is a collector's treasure, in part because the images were printed on heavy photographic paper and glued on to the pages where they were described by the text (a printing technique known as a 'tip-in'). The contrast detail in Barnard's images matches the better efforts of image processing techniques today.

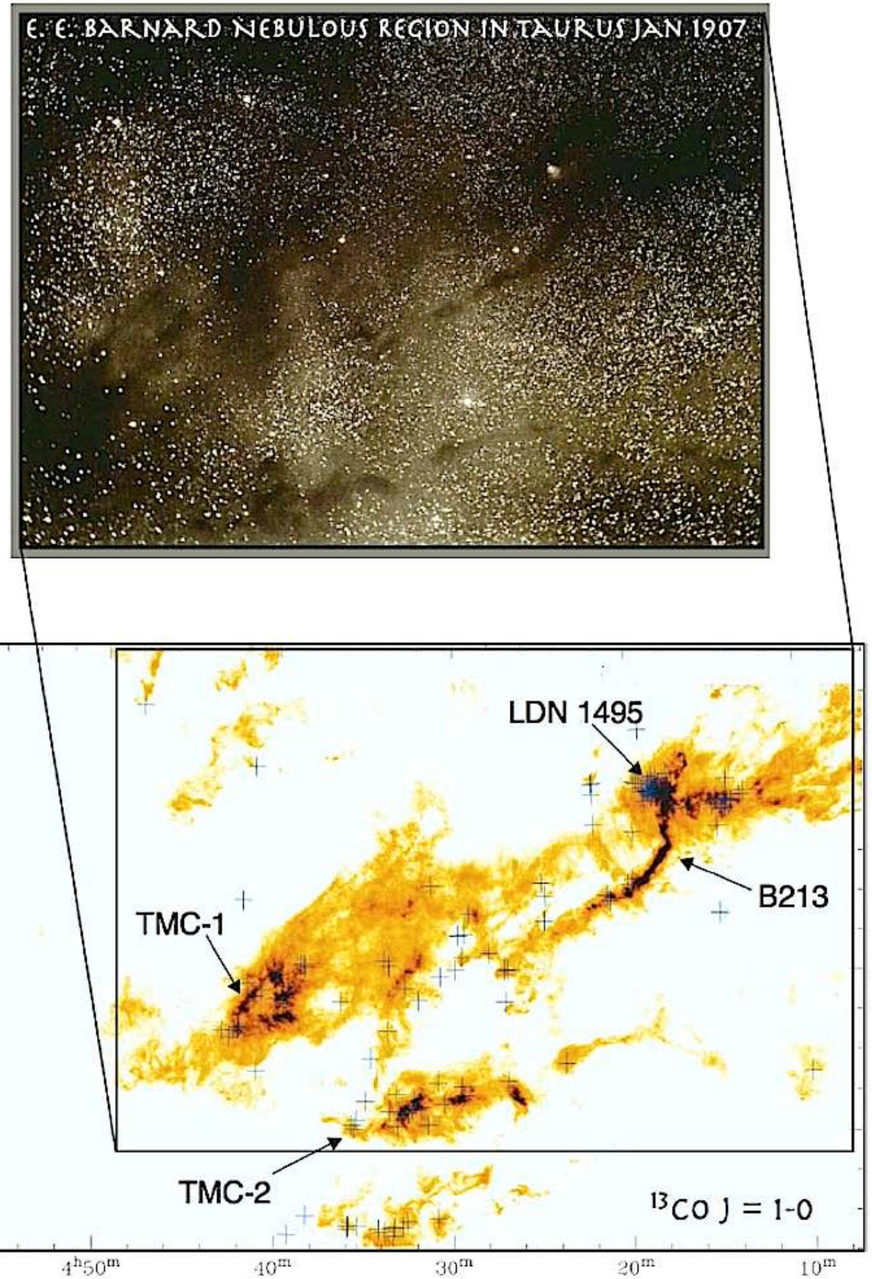
Barnard argued that his deep photographs provided increasing evidence that many of these dark areas were 'obscuring bodies nearer to us than the distant stars.' The overdense clumps were considered curious but unimportant clouds until the 1950s, when they were conclusively shown to be associated with star formation by Bart J. Bok in 1946 (Bok, B.J., *Centennial Symposia*, Harvard Observatory Monograph No. 7, 531948, not available online). Bok went further to demonstrate that star clusters were born in the compact, round dark blobs that now bear the name *Bok Globules.* (*Launhardt et al, 2010.*)

As equipment and technique improved steadily from 1950s through the 1970s a picture slowly emerged in which dark clouds were known to be a vital part of the gas/stellar dynamics of galactic behaviour. At phase scales of several parsecs or more, clouds were observed to be predominantly filamentary structures constantly barraged by high-velocity turbulent shocks. Over time the disruptive shocks were quenched by powerful magnetic fields. Magnetic pressure overcomes turbulence pressure, decreasing the ambient energy field. Large parcels of the gas go subsonic. Stars can form out of free-fall collapse if their ambient energy field is subsonic. At gas densities above $N_H > 10^4$ cm^{-3} gravitational energy surpasses the gas's internal energy density. The cloud free falls rapidly into protostars.

* This easily downloadable 2.8 MB PDF is a wonderful read. It contains some of the most exact at-the-eyepiece observational astronomy writing available. Barnard clearly enjoyed his eyepiece time. The plates which begin on p.25 reproduce acceptably in PDF, though readers need a bit of experience viewing dark nebulae to get a sense of the startling intensity of the dense blacks in the original book.

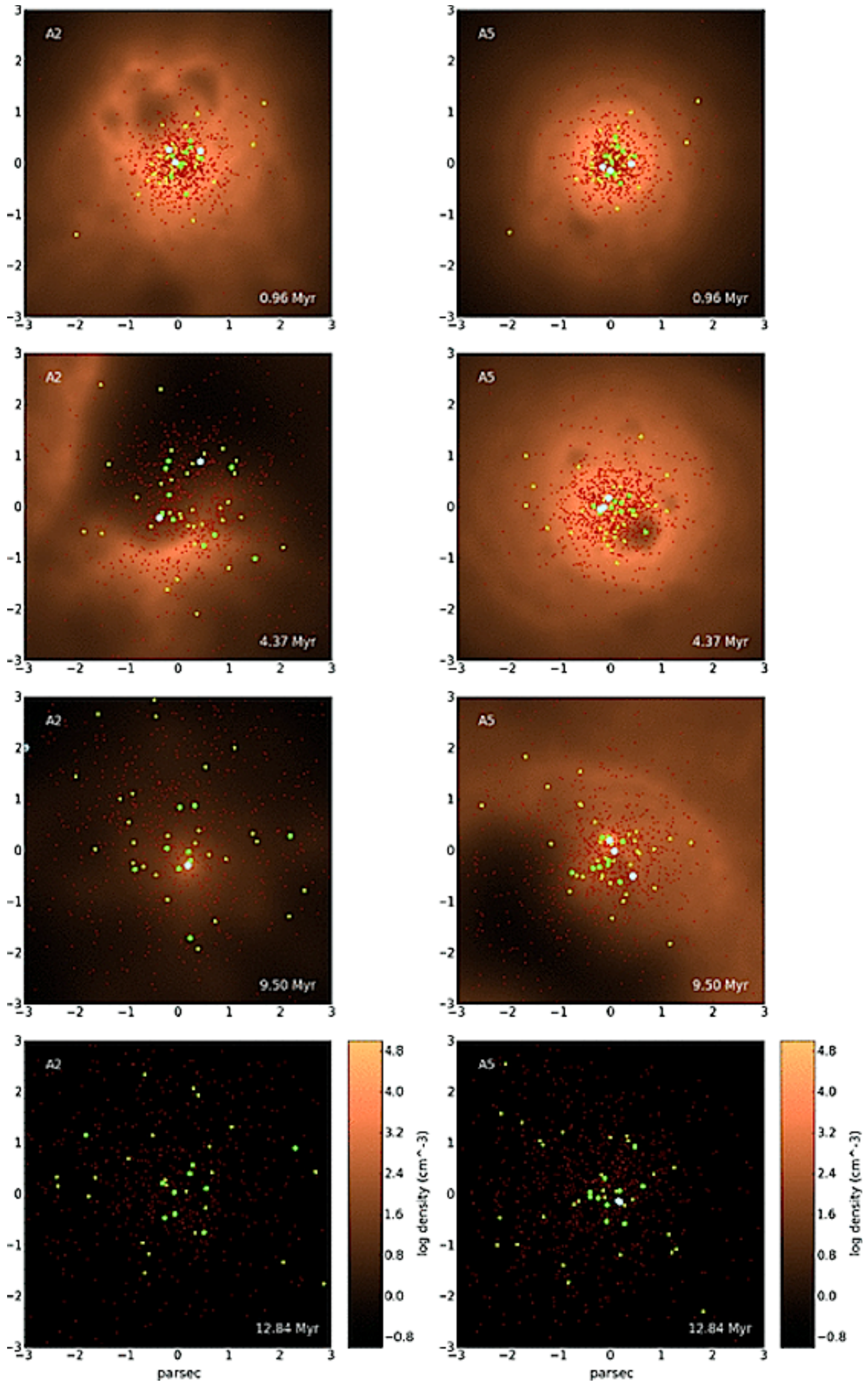
Starting in the 1960s the technology of modern infrared and millimetre-wave astronomy detailed ever more clearly the relation between dark clouds and the formation of stars and planetary systems. A key discovery was that complex molecules such as CN (cyanogen), OH (hydroxyl), and CO (carbon monoxide) were being made in space. Among them was the key molecule needed to initiate the complex reactions of astrochemistry, HII. HII is simply ionised hydrogen (*see this interactive example of the process*). Astronomers conventionally use the designation HII; other scientific disciplines use H^2. One reason is that the term H_2 designates molecular hydrogen. A typo that gets H^2 and H_2 wrong can ruin a lengthy calculation.

Molecular clouds are dark not because of their hydrogen molecules; they are dark because of their enormous populations of tiny soot-sized dust grains that absorb starlight. Dust grains tend to first aggregate atoms on their surfaces and then congregate into closer proximities. When they gather in quantities large and compact enough to block



Right: Taurus Molecular Cloud Complex.

Top: The Taurus Molecular Cloud was first imaged by E. E. Barnard in1919. He wrote, 'Very few regions of the sky are so remarkable as this one. This cloud is one of the most important of the collection for it bears the strongest proof of the existence of obscuring matter in space'. *Bottom:* B211 and B213 clouds in the Taurus Complex, courtesy of the Observatories of the Carnegie Institution of Washington. *Bottom:* ^{13}CO J=1–0 submillimetre-band emission map of the same region. The orange colour represents hydrogen gas insufficiently dense to collapse into a filament or cloud; this gas will eventually dissipate back into the Galactic disc for future recycling. The brown-black regions are clumps or cores collapsing into star clusters. The colour scale ranges from 0.5 to 10 K km s^{-1}. At only 140 pc or 430 ly away the Taurus Cloud is the nearest star-forming cloud to Earth. (*Watch the Wiki video pan across the cloud here.*)



light, they become the dense dark clouds that William Herschel expostulated to his sister Caroline.

By 1975 astronomers knew that the precondition for complex chemical structures (including us) was the freeze-out of HII molecules onto cold dust grains. (Weinreb et al., *Nature* 200:829 1963, and Wilson et al., *Astrophysical Journal Letters* 161:L43 1970).

Space has been with us a long time, and it's going to stick around for an even longer time. Even after thirteen billion year of nonstop stellar gas guzzling, an incalculable number of atomic hydrogen gas clouds dot the universe in the form of tenuous self-bound HI gas clouds. They are referred to as CHVCs or Compact High-Velocity Clouds. They have existed nearly untouched since the earliest epochs of the early universe. Dark clouds feed future galaxies since CHVCs are the primary source of fresh, pristine gas on which galaxies continue to thrive. Hydrogen is converted to helium and all the other elements via the atomic reactions inside stars, so if star formation is to continue there must be a continuous supply of fresh fuel from deep space. Without it our Milky Way would run out of gas in 2.6 billion years.

When a CHVC approaches a galaxy, it is absorbed into the galaxy's halo. That cools the halo ever so slightly, and, being now cooler, the halo contracts a bit to retain its disc–halo equilibrium. The process is called *virialisation.* A portion of the incoming gas cloud does retain its

Left: Dark clouds can be brutally cold inside. At visual extinctions greater than $A_V > 1$ mag) so much starlight is removed that temperatures in the centres plummet to within a few degrees of the 2.73 K cosmic microwave background. A few nearby dark clouds have become so dense they absorb even the CMB radiation; their cores drop to 1 K. At such cold temperatures there is virtually no internal energy to resist gravitational collapse into a star cluster. In this numerical or *N*-body simulation, two different initial densities produce different collapse rates and internal distributions. *Source:* Pelupessy & Portegies-Zwart, 2012.

shape. Slowly it descends toward the disc. The densest part elongates into a comet-like structure, which flattens once it hits the dense disc. Once hydrogen enters into a galaxy disc, things change rapidly and violently. A CHVC is soon disrupted and its once serene life far out in space becomes just another tidbit of hydrogen tossed hither and thither by every force in the lexicon of physical dynamics. Perhaps one day it will be part of another giant cloud that collapses into a star cluster or association of them. Perhaps it will remain a wanderer forever.

Time to head out to the eyepiece

Dark nebulae are stellar chocolates. They're not much on the outside, but wow on inside. For many observers light pollution eats them before you can open the wrapper. Half a magnitude of LP can drain the thrill out of all but the densest of them. In visual 6+ skies and a good pair of binocs, dark nebulae acquire an intensity that surpasses the emission sky. In southern skies when the Sagg/Sco/Lupus dark nebulae loom directly overhead the darks look like a crumpled black lace doily over a river of diamonds. In a pair of 10 x 50 binocs the Coal Sack becomes a tissue-thin balloon in which one can see both the inside and the outside — an illusion, of course, but oooohh what a pretty one. It's uncanny to see it as a ball of ragged tatters floating there, like a still frame from a super slow-mo punctured balloon shredding itself to pieces in front of a wall of stars.

Vinyl record collectors say that the sound detail of their old pressings has a 'presence' that CDs do not. Dark nebulae have a 'presence', too. They can be as textured visually as Brahms is to the ear. Pan across the *Lupus 3* or the molecular murk that tints NGC 6726 a silvery blue before it streams into the inky puddle of SE Corona Australis, and the mood of the view goes from glittery to dusky to icky to cimmerian to gloom. It's a creepy place to be. It's everything stargazing is not. The sky looks like a wriggling spiderweb on quicksand in a gyre in a dungeon. Move away into the stars again and it's like taking a shower. Whew! All clean again.

Imagine for a moment that there you are at the eyepiece. What would you see if *you could see what the Universe does on its own time scale*.* Night after night, our wondrous eyepiece entertainment keeps us lifting our faces to the sky. By day we nourish our minds with them. Dark clouds are among the most astrophysically complex structures in the Galaxy — orbital mechanics, the cosmochemistry lab of supernova remnants, the Janus faces of electricity and magnetism, urantology (space weather). Fluid dynamics describes states of gases so dense they are almost completely stripped of their electron shells and behave like fluids. All the laws of mechanical heat — convection, advection, conduction, adiabatic heating and cooling — are right there in our eyepiece balcony as we watch the drama of the sky. We can't hear the song the universe sings because it's 50 decibels below Middle C. It's hard to follow the cosmic plot line because the 'instants' through which the stellar actors move are 100,000 years. Indeed, astronomers who specialise in star cluster use the term 'instantaneous' as shorthand for 100,000 years. Galactic astronomers consider 'instantaneous' as a million years. Cosmologists think instants are 100 million years.

Even aerodynamics gets into the cosmoquest of a particle in space trying to find a peaceful place to settle down. We can err if we visualise

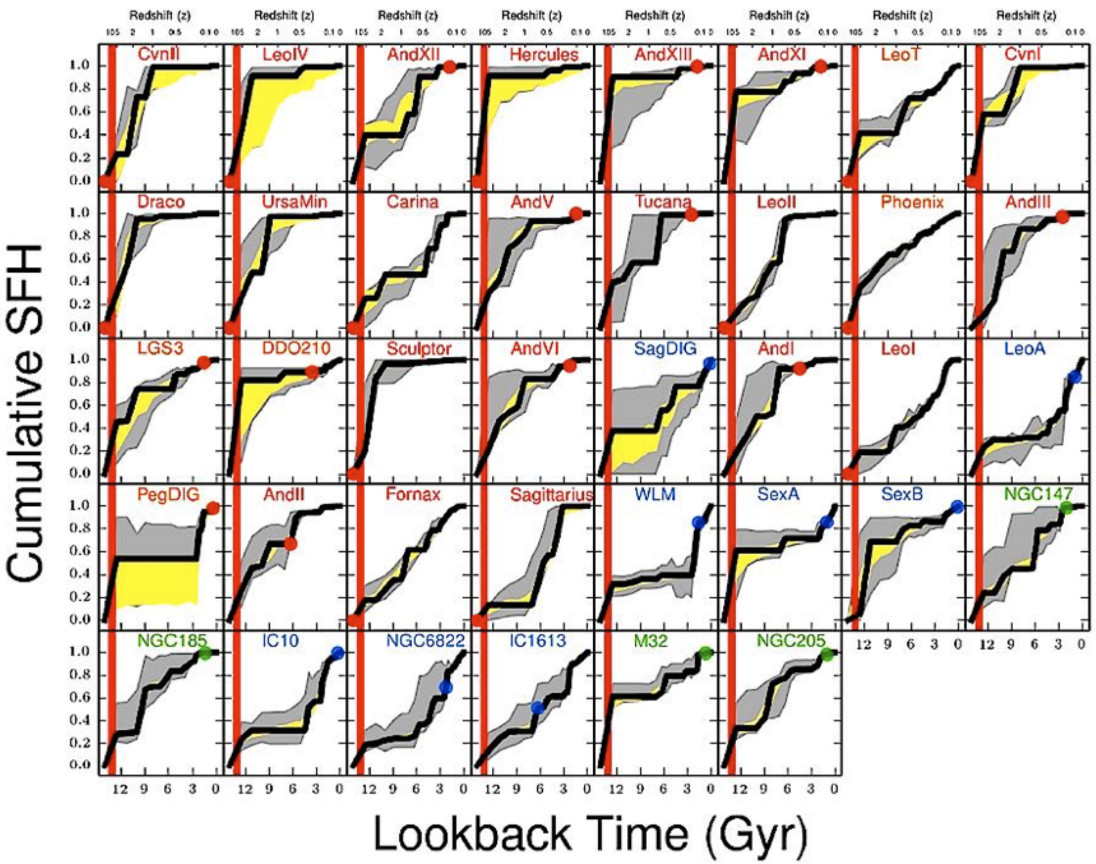
* This *Illustris* simulation box is 10 Mpc on each side, 495 million years in time, at $z = 0$. You can find them *here* and *here* (the stills are above, the sims below). Readers can calculate the exact halo mass, stellar mass, gas mass, and U-band luminosity *for any point on this sim here*.

objects as hurtling hypersonically through a still medium; sometimes the medium streams hypersonically past them. The energy perturbations of shock fronts are a hydrodynamist's paradise. They are the battleground of matter density -vs- energy density in a combat neither side can really win. The winner is always entropy and entropy never gives anything back.

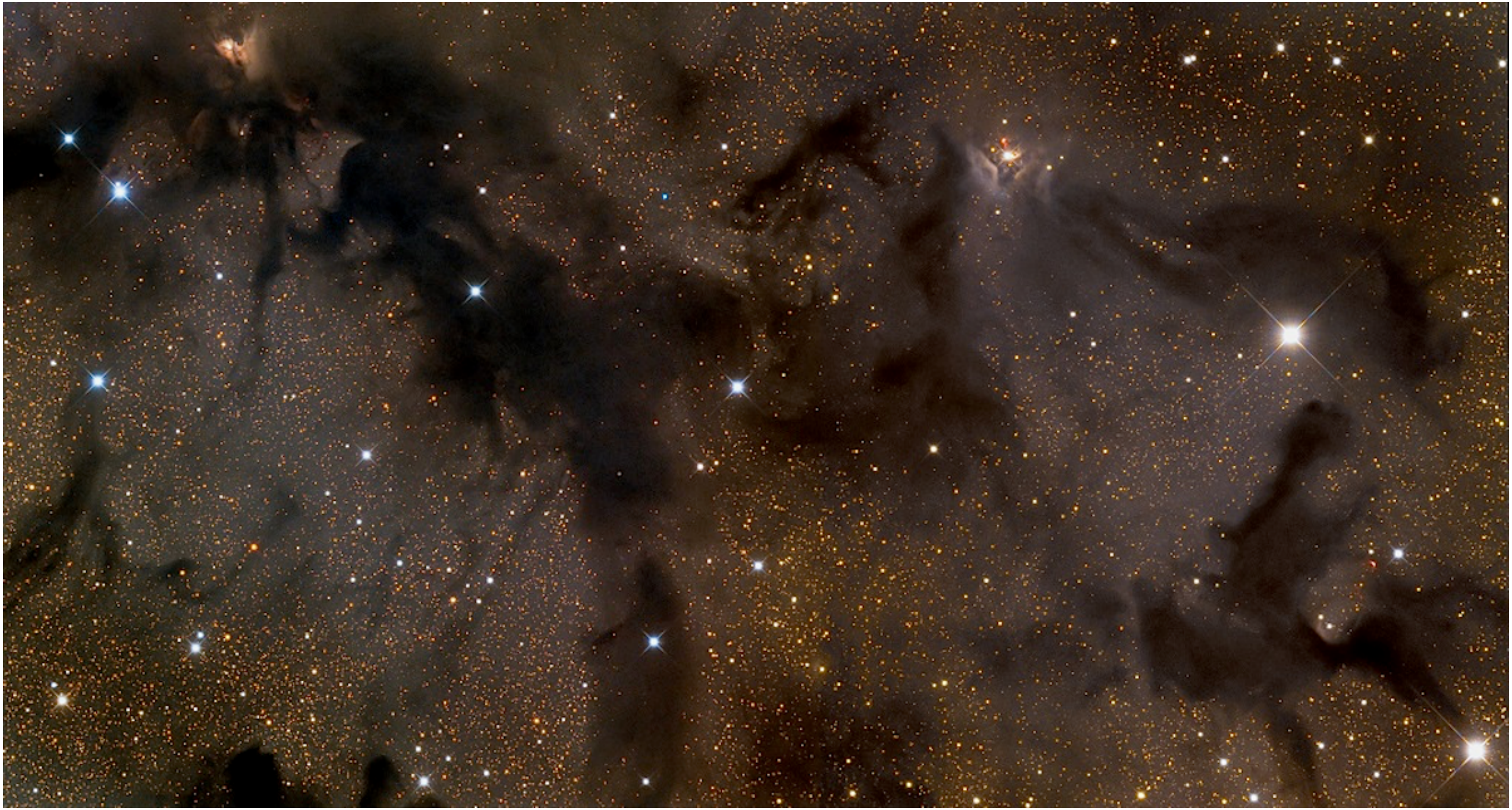
Most molecular gas in the interstellar medium (ISM) resides in giant self-bound clouds (GMCs), with masses of ~10^5 solar masses tens of parsecs in diameter, whose densities of averaging N_H 100 cm^{-3}. (N_H is shorthand for 'number of hydrogen atoms'.) GMCs are inhomogeneous. Visually they appear as filamentary webs dotted with dank musty clumps. Their typical mass is on the order of $10^3 – 10^6\ M_\odot$, average sizes of ~1 pc^3, and densities of $10^3\ N_H$ cm^{-3}. They are the coldest places in the universe. Clumps can be contrarily inhomogeneous, clotted with pocket-like overdensities as high as N_H 10^4 cm^{-3} and underdensities as low as N_H 10^{-4} cm^{-3}.

In the really big picture, lasting multiple billions of years, the complete cycle of star formation recycles roughly 99% of the original gas mass back into space. During the relatively brief ('instantaneous') star formation epoch, only around 3 to 10 percent of the original gravitationally bound gas mass condenses into stars. Once the stars are made, sooner or later they eject nearly all their unused natal mass back into space, mainly through UV radiation from hot massive stars and particles ejected from their hot surfaces. Our Sun's coronal mass ejections that raise such holy hell with our electrical systems on Earth are piffles compared with what an O or B star can do. We would be toast so fast we wouldn't feel it.

Even when stars spectacularly blow up, they re-seed their galaxies with more stuff to make into stars. Because each stellar recycle leaves traces of heavier and heavier atoms, we can build up a history book of almost any galaxy's star formation history.



Star formation histories of local group dwarf galaxies, from *Weisz 2014*. Dwarf galaxies are especially sensitive to the amounts of ambient gas around them. Remote dwarfs tend to have made all their stars very early and then remain quiet. Dwarfs closer to large galaxies undergo steady but irregular mass injections from giant CHVCs which fuel new starbursts throughout their evolution.

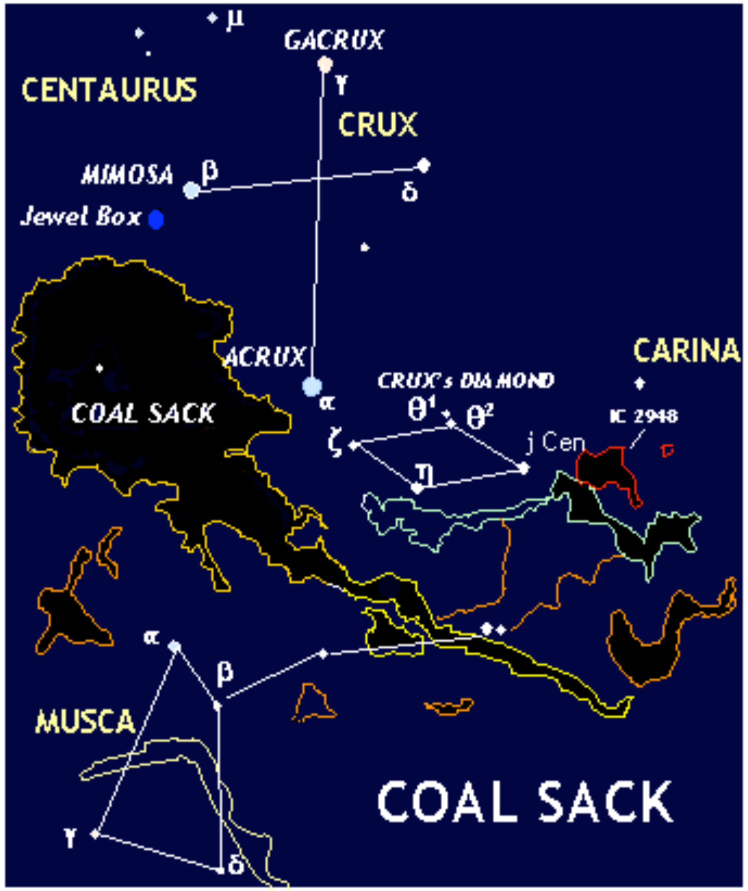


Lynd's Dark Nebula in Aquila (LDN 673) is a dense, turbulent dark cloud complex in the centre of the Aquila Rift, some 300 – 600 light-years from Earth. It is about 7 ly across. The Aquila, Vulpecula, and Cygnus Rifts comprise just part of the much larger Great Rift. LDN 6573 is a loosely associated stream of molecular dust clouds located between the Solar System and the Sagittarius Arm of the Milky Way. The Great Rift appears as a dark lane that splits a dark canyon along the crowded plane of our Milky Way galaxy into two as seen from Earth. Each cloud contains about 1 million solar masses of plasma and dust. LDN 673's dusty molecular clouds contain enough raw material to form many thousands of stars. Visible indications of energetic outflows associated with young stars include the small red tinted nebulosity RNO 109 (at top left of this image) and Herbig-Haro object HH 32 (above and right of centre). Learn more about Beverly Lynd's dark nebulae here: *1*, *2, 3*, *4*. Read *more about Beverly Lynds here*.

Coal Sack

The Coal Sack is a big softie. In that whole, huge blob of dark, only one of its cores will form a star cluster. The rest will be recycled into space. The unused gas can take a hundred million years or more to glue its way into another dark cloud. Perhaps a given parcel of gas will be lucky enough to compact into the burning-bright stage, but the chances are 9-to-1 it won't.

The Coal Sack is the dark blob between Hadar/Beta Centauri (upper left off the image) and Acrux. Unfortunately for urban dwellers the Coal Sack is obscured by even modest amounts of light pollution. In country skies the region is startlingly obvious. It looks like the deep hole in the firmament that so astonished Herschel. In reality the Coal Sack it is just another giant dustbag of obscuration that just happens to lie in the Carina Arm in a location noticeable to us. Binocular inspection finds the Coal Sack edges to be ill-defined. Shift your attention to the stars behind it and it suddenly seems 3-D, a bag of feathers in front of a fan. The image on the next page parses the Coal Sack into its densities. In binoculars the Coal Sack is the lacemaker of Crux. On the darkest night the main body oft his dark cloud slowly diminishes to the south-west.



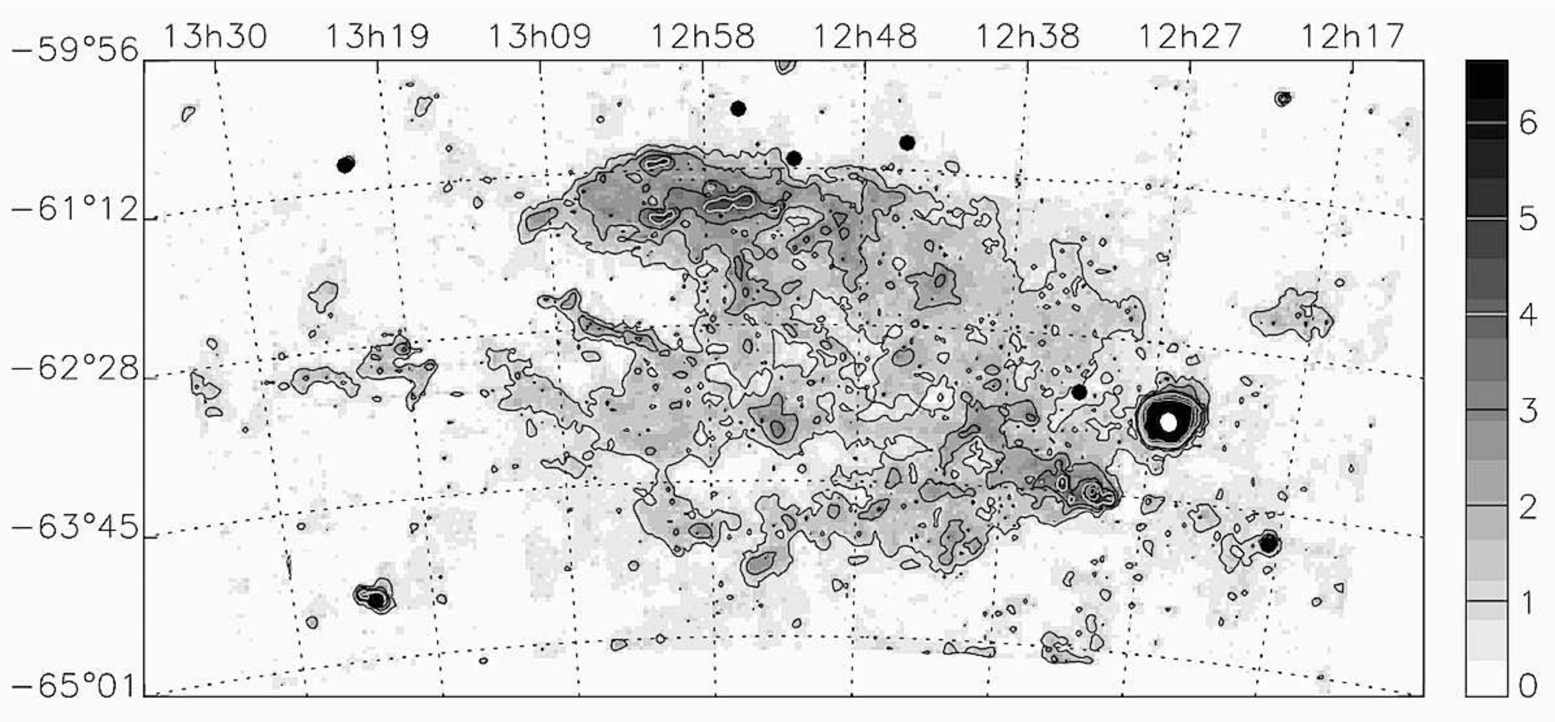
Below Acrux it dwindles into a slender stream of blackness.In reality this is a longitudinally compressed filament shaped by a magnetic field. Eventually the overall structure descends further SW until it loops up again towards the red HII emission nebula IC 2948, finally fading completely near the famed Eta Carinae Nebulae NGC 3372. We do not yet know whether this structure exists in phase space the way it appears in visual space. The term 'phase space' is shorthand for viewing a particular field using criteria other than visual appearance. Dimensional phase space is how the object occupies 3-D space. Metallicity phase space would be a map of the object in a specific set of metal abundances, e.g, the [Fe/H] ratio commonly used to age-date an object. Velocity phase space is the pattern of internal velocities made by specific parcels moving in 3-D in relation to each other and to the background.

Back to the Coal Sack, other wisps of dark nebulosity surround the area as well. A prominent one is is the Dark Doodad Nebula (see below) which elongates down the west side of Musca to the south.

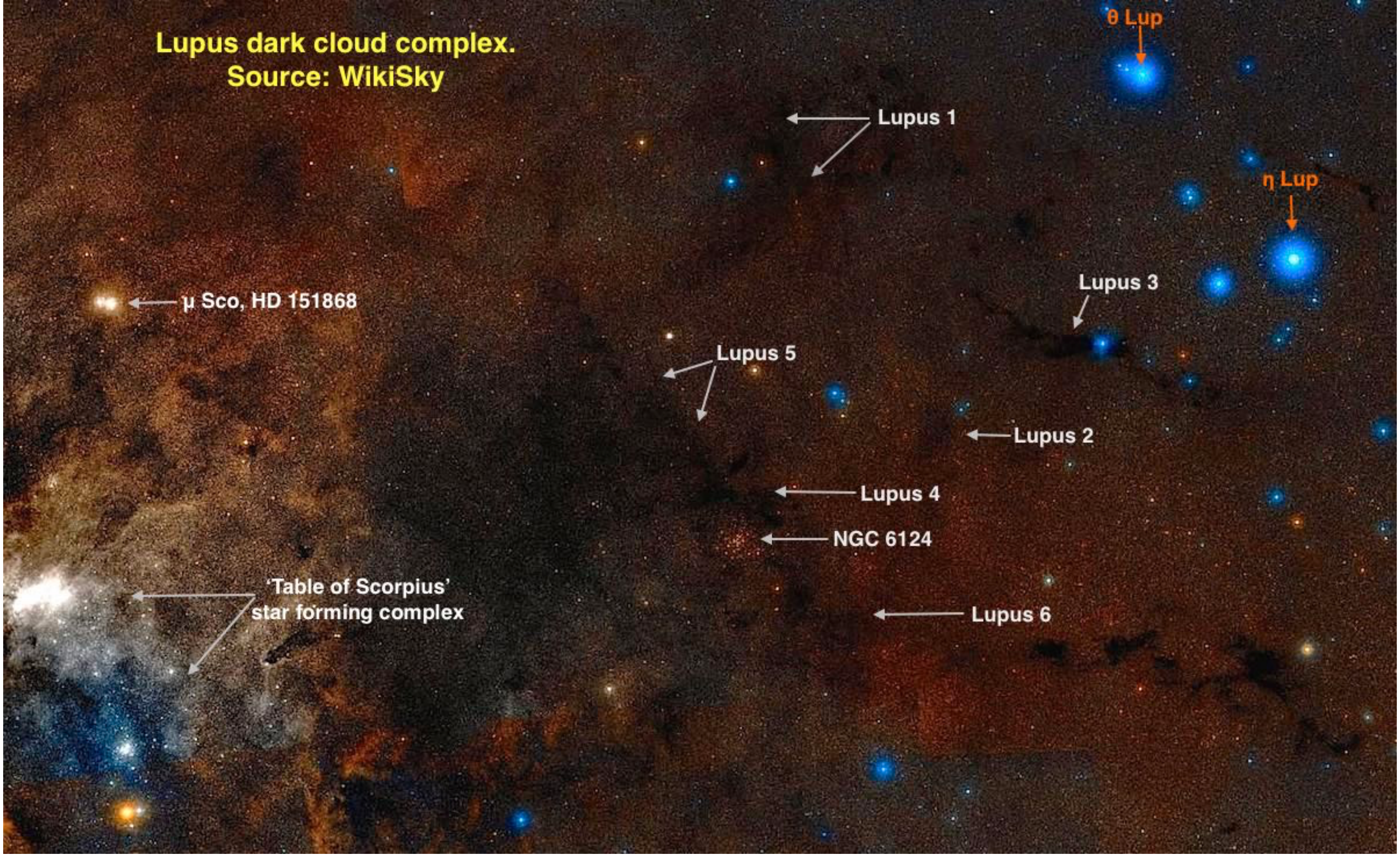
If your eyes are acute enough, you can possibly notice the faint 6.5 magnitude star within the nebulosity (white dot above the word 'Coal' in the schematic). This is *HD 110432 (BZ Crucis)*, a furiously fast-rotating gravitationally unstable Be star of 12 $M_{\odot}$. The star's spectrum shows very rapid variations on very short times scales (e.g., across just one night of observing). These are attributed to very brief, irregular strongly magnetised bubbles blasting high-velocity holes in the star's circumstellar clouds. Imagine life in the middle of a boiling tea kettle. If the Sun behaved like this we would be treated to a lifelong fireworks show all across the entire sky, day and night.

The Coal Sack is estimated to be 190 parsecs or 620 light years from the Sun. The Coal Sack's nebulosity was first recorded in 1752 from the Cape of Good Hope by Abbé Nicholas-Louis de la Caillé (1713–1792), who wrote in his '*Mémories de l 'Academie Royale des Sciences', 1755* (p. 286–296), 'One might again include the phenomenon which strikes the eye of those who observe the Southern sky; a space of almost three degrees extent in all directions which appears as dense blackness in the eastern part of the Southern Cross. This appearance is caused by the intensity of the whiteness of the Milky Way which encloses this space and surrounds it on all sides.'

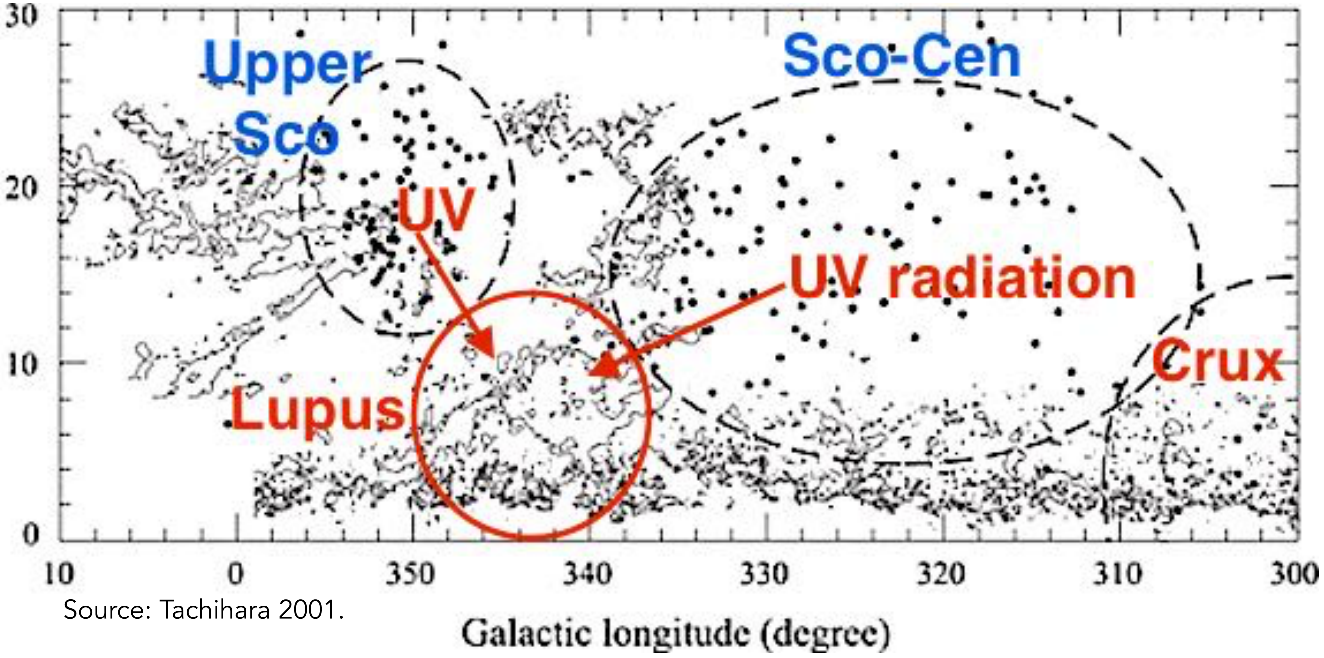
Legend has it that the moniker Coal Sack derives from drovers or miners in the Australian outback. At night these men described this region as 'black as coal' compared to the surrounding bright Milky Way. Sir John Herschel advanced an alternative explanation of the origin of the name, saying it was used in the early 1800s by sailors when visiting the southern seas. Occasionally one comes across a reference to the Coal Sack as the Black Magellanic Cloud. You name it, you own it.



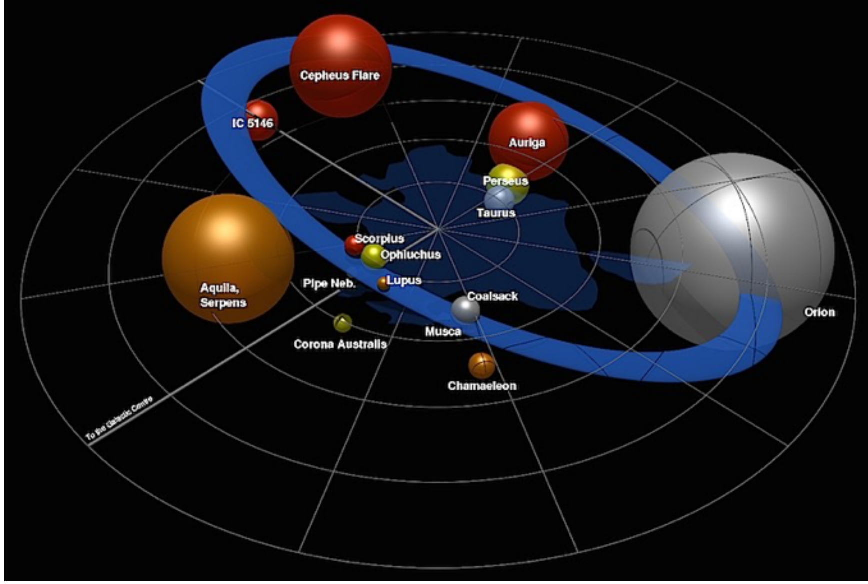
Extinction map of the Coal Sack from *Cambresy 1999* (Fig 4). The densely black pocket on the right is the only clump compact enough to collapse into a star cluster. As the round shape suggests, the collapse is underway even now. The Coal Sack is roughly 150 pc (490 ly) in diameter, but it comprises only 1.4 x 10^4 $M_\odot$ of gas. Its maximum extinction in the darkest core is A_V 6.6, which would dim starlight from behind by 3980 times. Dramatic as this scene appears (and is even more dramatic in the sky), the cluster that eventually forms will be a rather modest one. The rest of the gas will continue doing what it is right now: dissipating back into the spiral disc. The poor thing just didn't get its gravitational act together. Indeed, many nascent star forming clouds never make it to stars. And we think *our* weather is so fickle!



The Lupus molecular cloud complex covers such a large section of the sky that it has not yet been fully examined with a molecular line survey. There is considerable star-formation activity at various ages among the Lupus clouds. This is attributed to an interaction with a very large expanding HI shell that reaches as far as the ρ Oph cloud. In a 1996 ^{13}CO survey Tachihara et al. found a molecular outflow in the Lupus 1 cloud. In 1993 Gahm et al. observed the Lupus 2 cloud in ^{12}CO, finding multiple-velocity components in the line of sight. Hara et al. studied the region in 1999 using $C^{18}O$ observations, finding 36 embedded dense cloud cores. Some cores that are starless. These typically have larger line widths than similar active star forming regions,a sign that their molecular gas is disrupted by strong turbulence. Turbulent shock waves interacting with each other counteract the inherent self-gravitation of molecular cloud cores. (*Source: Tachihara et al. 2000a*).

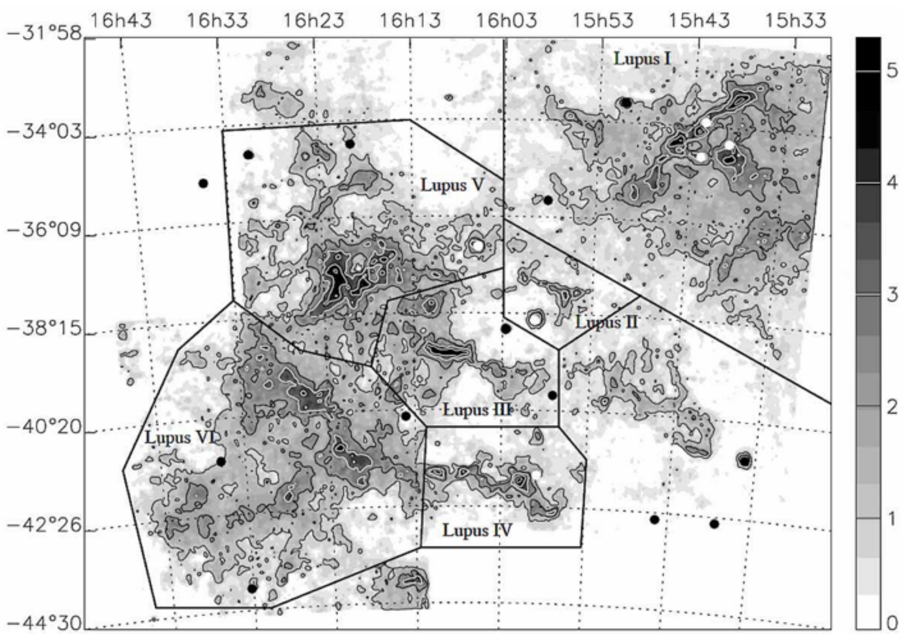


Source: Tachihara 2001.

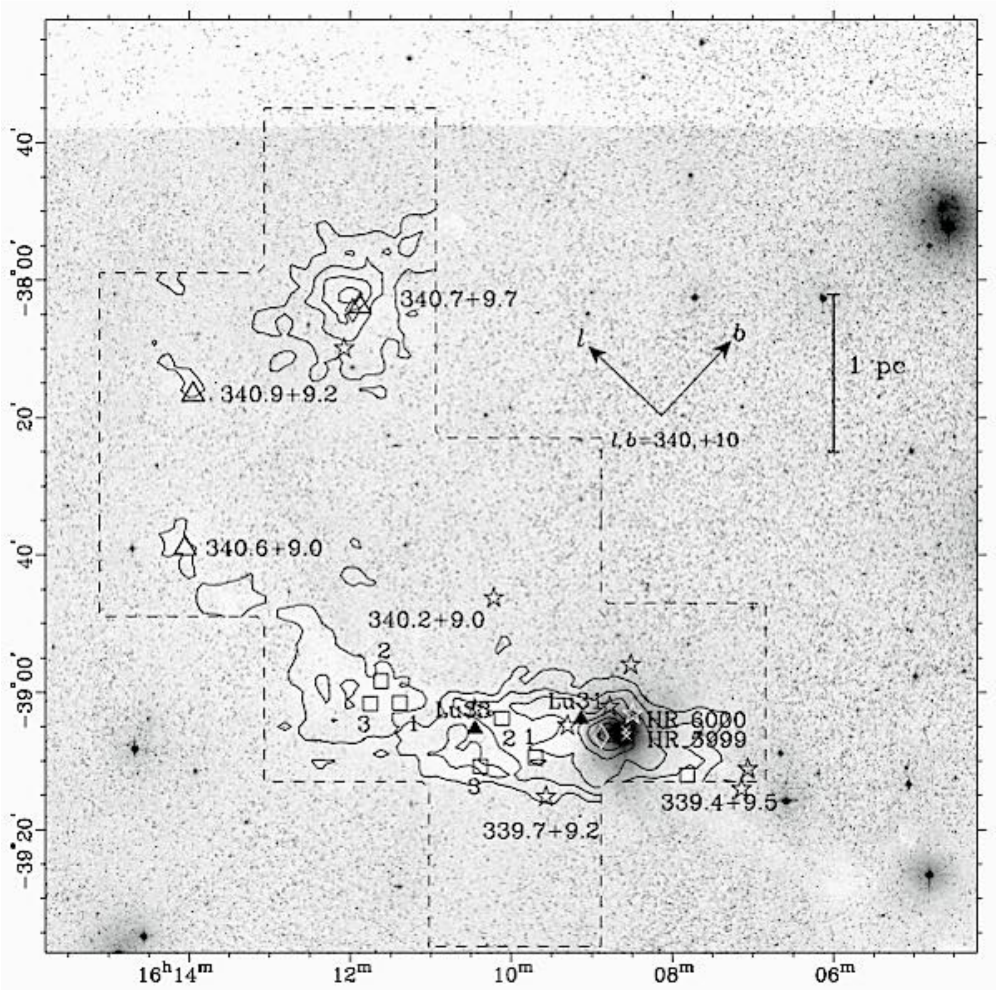


Schematic of Gould Belt OB and dark cloud associations. Gould Belt is in blue. *Credit: J. Kirk & V. Konyves*.

The Lupus clouds are part of the Scorpius-Centaurus OB group, one of the best studied of the OB associations. Sco-Cen is a huge complex — over 300 early-type O and B stars spanning nearly 90° in Galactic longitude at an average distance of ~140 pc (456 ly) from us. There is a strong likelihood of physical interaction between Lupus and Sco-Cen. In turn, Sco-Cen, the Perseus OB2 association, and the Orion complex are the principle structures comprising the Gould Belt. The Gould Belt is an extended planar arrangement of OB associations that dominate the the energy density field of the solar neighborhood out to ~600 pc (1956 ly). The Belt's outer apsis (furthest extent) lies not far from the Lupus clouds. The Lupus assemblage itself lies at a relatively high Galactic latitude, suggesting that it did not originate from infalling clouds but rather local pressure from the nearby massive associations. The Sco-Cen region is an assemblage a number of distinct groups. The evidence that Lupus is associated with them is partly seen in age-luminosity bins observed among the photometric ages of both group's stars. At 14 Myr the Lupus clouds occupy a gap between the Upper Scorpius and Upper Centaurus-Lupus age bins, This suggests that the Lupus clouds are participating in a more recent episode of star formation than the Upper Sco and Sco-Cen. The region surrounding the Lupus clouds is devoid of the early-type O and B stars found in those groups. Moreover, the Lupus clouds are not presently undergoing high-mass star forming activity. The abundance of so many OB stars in the nearby Sco-Cen implies that Lupus lies in Upper Sco and Sco-Cen's intense ambient UV radiation field. High-energy radiation increases the mechanical energy already being injected into the Lupus clouds by stellar winds from the nearby OB stars. All these energy sources have played an important role in the origin and evolution of the Lupus cloud group.



Lupus 3 molecular cloud complex located 184 pc away at RA 16h 08m 34s, Dec –39° 05′ 35″. The double star in the middle is HD 144667–68, some 240 PC away. The blue reflection nebula shows the effects of foreground scatter, when light from a distant source is reflected at shallow angles off tiny dust particle in between the source and our eyes. To the left, the soft edges of the elongated absorption clouds are evidence that magnetohydrodynamic quenching is slowing the swirling maelstrom of supersonic turbulence associated with cloud collapse. The intense darkness of the filament centres is caused by molecule densities greater than 10,000 particles per cubic cm plus the large amounts of dust in HII clouds.



Astronomers use the term "extinction" as a unit of measure. They cite the number of hydrogen atoms in a cubic centimetre from 1 to 10,000. At N_H 10^4 cm^{-3} the gas density is high enough to 'extinguish' a star or galaxy on the far side by one magnitude. At densities of 10^4 cm^{-3} astronomers use extinction in visual magnitudes as a calibration measure. The extinction in the Lupus 3 core is 25.5 magnitudes (roughly 62 million times fainter than a 6th magnitude star). At such density levels the star enters the protostellar phase and generates internal heat from gravitational contraction. *Source:* Tachihara et al 2001a.

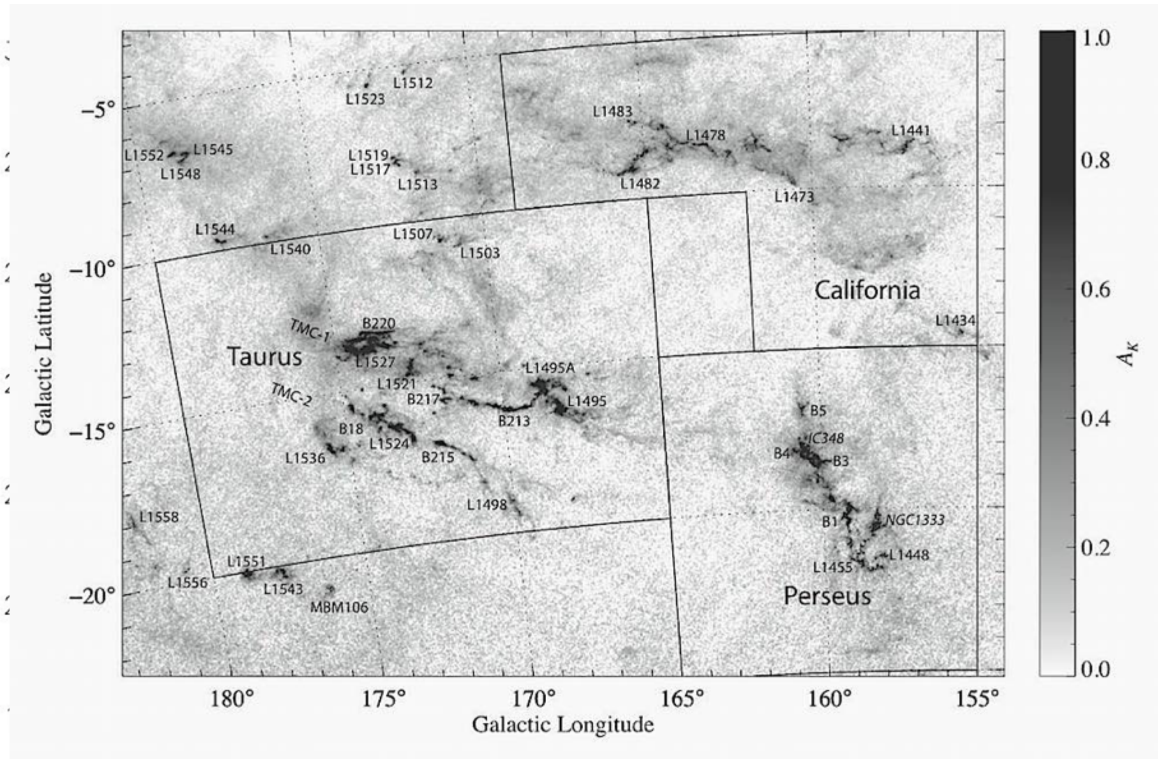
Left: Optical image of Lupus III in Tothill et al 2009, Fig 2. The contours are density levels of ^{13}CO, a carbon monoxide molecule in which the carbon is the isotope of normal ^{12}CO with one extra proton, making it ^{13}CO. ^{13}CO is produced in the carbon-fusing cores of AGB stars that were already rich in carbon from previous generations of other AGB stars. The neutron surplus in such stars can pack an additional proton into the nucleus of a totally or near totally ionised carbon atom if the core temperature is high enough. In the absence of the electrostatic barrier of an electron shell (the Coulomb barrier), the only barrier a proton has to overcome to penetrate a Carbon nucleus is the Strong Force. The temperatures in AGB fusion cores are well in excess of 100 million K. At energies that extreme a footloose proton can cram its way into the nucleus before the normal rejection response time of the Strong Force, which exists in part to keep them out. Here is a case where the speedy bird gets the worm. The contour lines mark gas temperatures of 2, 4,...12 Kelvin per km s^{-1}. (The crosses are stars.) This map covers only the Lupus 3 region; the Tothill paper analyses the entire Lupus molecular complex. The authors were able to observe the ^{13}CO J=1–0 molecular transition. The J refers to the near-infrared (NIR) spectral band. The 1–0 refers to an electron emitting a photon as it drops from the first valence shell to the ground state. The real info the authors were after was the HII mass in these clouds, because HII is the primary ingredient in gas clouds dense enough to collapse into star forming regions. By determining the HII mass the authors would know if the Lupus complex would form any more star clusters in the future. However, HII is a very weak emitter; data based on it alone would be inconclusive. HII is very often associated with carbon monoxide (CO) which is another by-product of the prolific molecule formation that occurs on dust grains. 'Prolific' in a molecular cloud can mean one new HII or CO molecule every 10,000 years or so. For space, that's fast. ^{13}CO emits more strongly in this band than ^{12}CO so the authors chose ^{13}CO as their HII tracer. By tracing the ^{13}CO emission levels, the authors could calculate the mass of the entire Lupus III cloud. In the end it came out to a rather timid $10^4\ M_\odot$ — much too low to form stars.

Eventually the myriad disruptive forces that occur in a spiral arm will dissipate Lupus 3 back into the thin medium whence it originally came. 'Easy come, easy go' is a useful philosophy in space.

Taurus

The Taurus Molecular Cloud (TMC) is a star-forming region located 450 light-years from Earth. The vast cloud complex is one of the nearest large stellar nurseries to Earth. It contains over 400 young stars.

The TMC contains numerous deeply embedded T Tauri protostars. These are very young low-mass stars still in contracting gravitationally. Some undergo a phase in which they eject narrow jets of gas at velocities of several hundred km sec^{-1}. TMC also has a large number of brown dwarfs, dark substellar objects that are too low in mass to sustain hydrogen fusion, so fuse hydrogen into deuterium instead. Brown dwarfs can be as small as 0.08 $M_{\odot}$, or 13 Jupiter masses.



Star formation is ongoing in the TMC. The cloud contains stars undergoing all the various stages of stellar evolution.

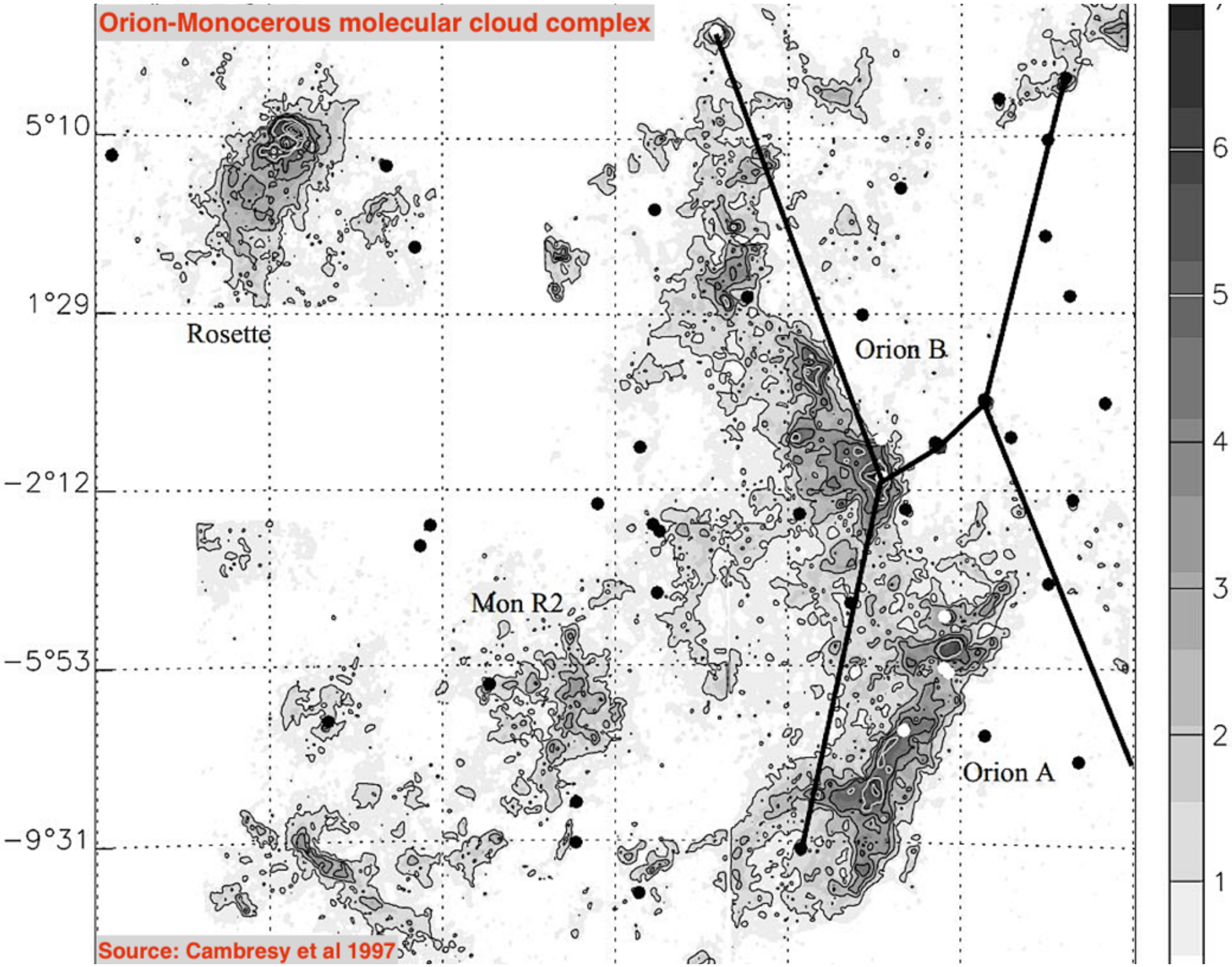
The Taurus Molecular Cloud contains the cold pre-stellar cloud Lynds 1544 (L1544). The ESO's Herschel far-IR and submillimetre space observatory detected the equivalent of more than 2,000 Earth oceans of water vapour liberated from icy dust grains by high-energy cosmic rays passing through it. H_2O forms on dust grains as hydroxyl (HO) molecules bond at the extremely cold temperatures within molecular clouds. The term 'water ice' means just that in space.

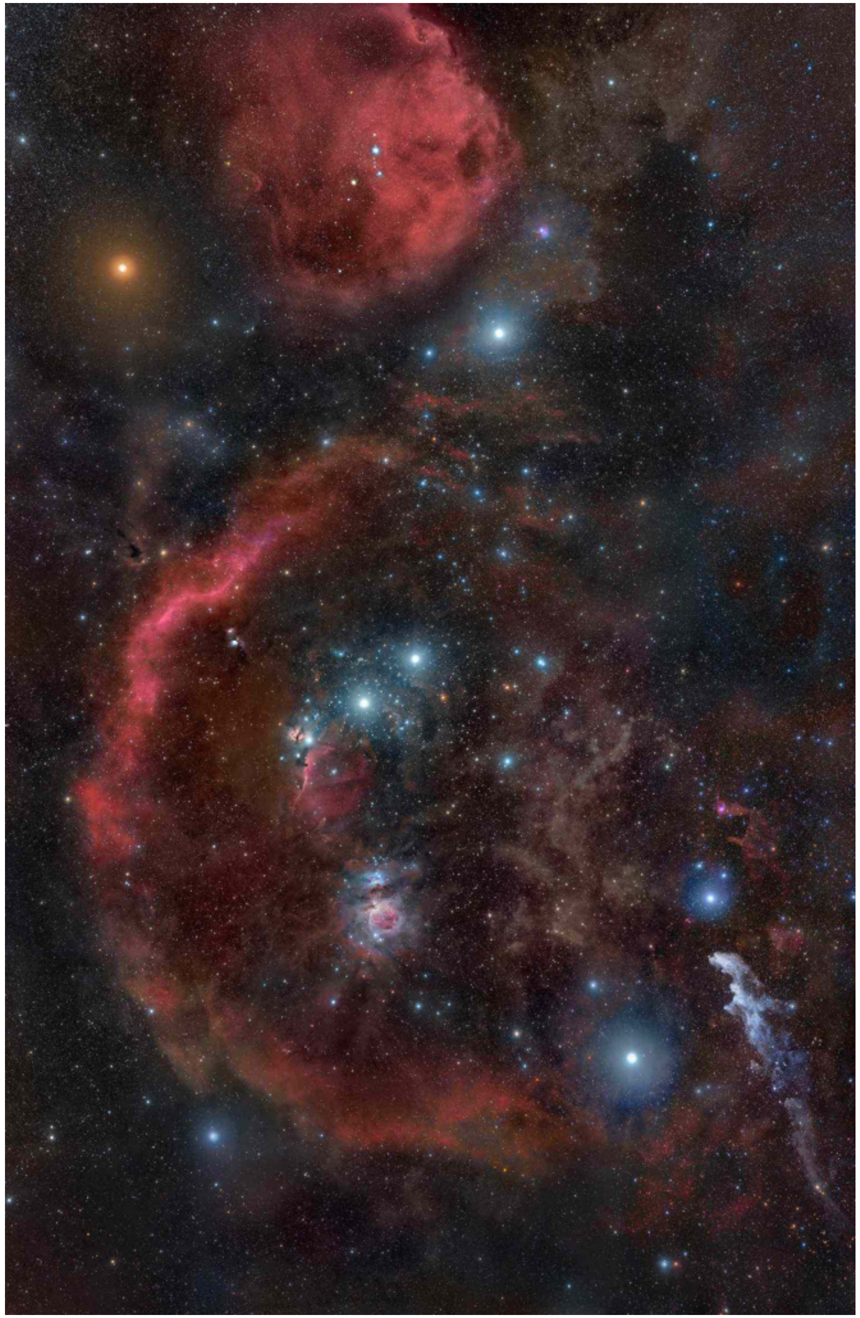
Lynds 1544 must have more than three million frozen Earth oceans' worth of H_20 to produce that amount of vapour. The Herschel observations also revealed that the water molecules are migrating towards the heart of Lynds 1544, where a new stars may possibly form. That indicates gravitational collapse is underway. There is enough material to form a star at least as massive as our Sun. Some of the H_2O in Lynds 1544 will go into forming the star, but the rest will be incorporated into the surrounding disk, providing a rich water reservoir to feed potential new planets.

There are no large stars to illuminate the Taurus Molecular Cloud. It is black in visible light but glows in the IR bands.

Orion Molecular Cloud Complexes A & B

Take away all those bountiful stars. Take away all the writhing beauties of nebulosity. Take away the billowy shock waves and magnetic tentacles. What's left? *Dust.* If we could put a Dust filter on our telescopes, this is what we would see in M42 and M43.





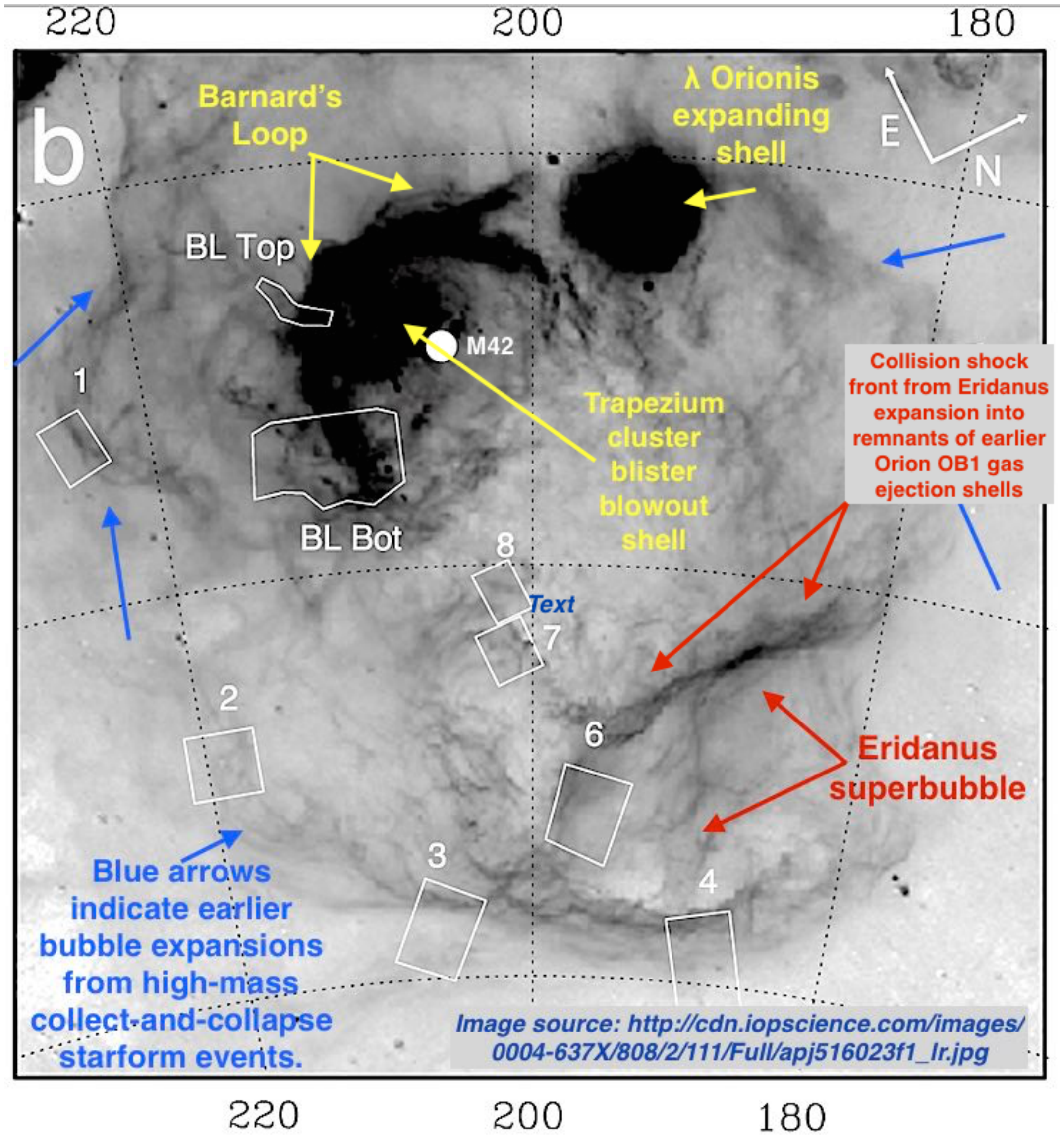
The multiband images on this and the next pages make very clear how limited is the evidence our visual observations provide for a complete understanding of the objects we see. Rogelio Bernal Andreo's panopticon image of Orion is spectacular, but provides little evidence of the time frame over which the image has evolved, from where, and in what way. It's an unfortunate fact that no matter how much we see with our eyes, it is <1% of what's there.

The Orion Molecular Cloud Complex is a giant bubble of interstellar gas and dust surrounding the Orion Nebula. At 1,450 ly distant and ~240 ly in dia.the OMCC contains M42 and M43, Barnard's Loop, the Horsehead Nebula, the Orion OB1 association, and M78 reflection nebulae, and the λ Orionis molecular shell that surrounds Orion's head.

Orion OB1 has three components: OB1a surrounds Orion's Belt (an obvious and beautiful cluster in binoculars). OB1b lies NW of the Belt stars (not shown in image here). OB1c surrounds the Orion's Sword cluster/nebulosity association. The stars of M42 and M43 are the youngest stars in the association. The Orion Molecular Cloud 1 (OMC-1) lies NW of the Trapezium.

The Trapezium itself is a vivid example of a blister-blowout bubble. These are a lopsided variant of the appx. spherical shell produced when a high-mass star-forming region emits intense UV radiation and high-energy protons from the surfaces of luminous stars. (When our Sun does this we experience aurora and EM spikes in electrical transformers.) Blister formations occur when a spherical shell expands against a pre-existing high-density shell; the expanding shell slows or even stalls, while the rest of the shell fills out into a sphere normally. In the Orion Nebula, the radiation blazing out of the Trapezium has blown out a shell easily visible behind it to the E, but the shell advancing in our direction has stalled, causing the Trap to appear glued to one side. In a lower-power wide-field eyepiece, if one stops looking at stars and instead takes in the entire emission region and a single entity, the bubble is seen to look like one. If conditions are right, in 3D.

Some 60% to 70% of the stars in the Orion Complex have dusty disks of the type associated with precursors of planetary systems. More evolved nascent planetary systems have been speculated to exist in proplyds and Herbig-Haro polar-jet emitting young protostars.

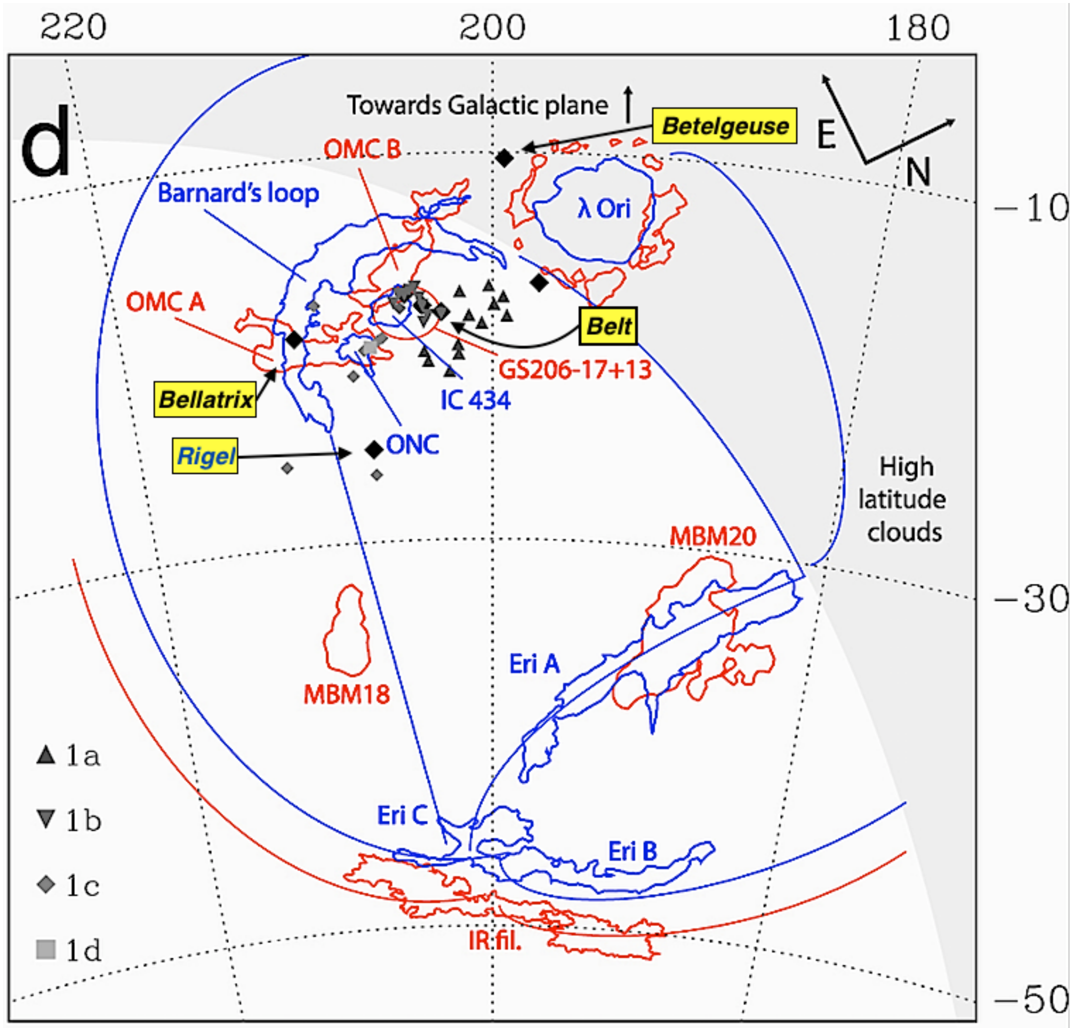


Source: Ochsendorf et al., *Nested Shells Reveal the Rejuvenation of the Orion-Eridanus Superbubble.* Astrophysical Journal, Volume 808, Issue 2, article id. 111.

The Orion–Eridanus superbubble is an expanding structure 20° x 45° on the sky. It is a series of nested supernova expansion shells. Each new SN generates a high-velocity bubble of its own, which is 'nested' within the earlier shells. The Eridanus Superbubble is an unrelated set of nested bubbles, which interacts with the Orion SSB along the shock front shown on the previous page. SN shells sweep up and compress any plasma gas the advance into. The expansion energy of the bubble is a combination of ionising UV radiation, stellar winds, and a progression of supernova (SN) explosions from the Orion OB1 association.

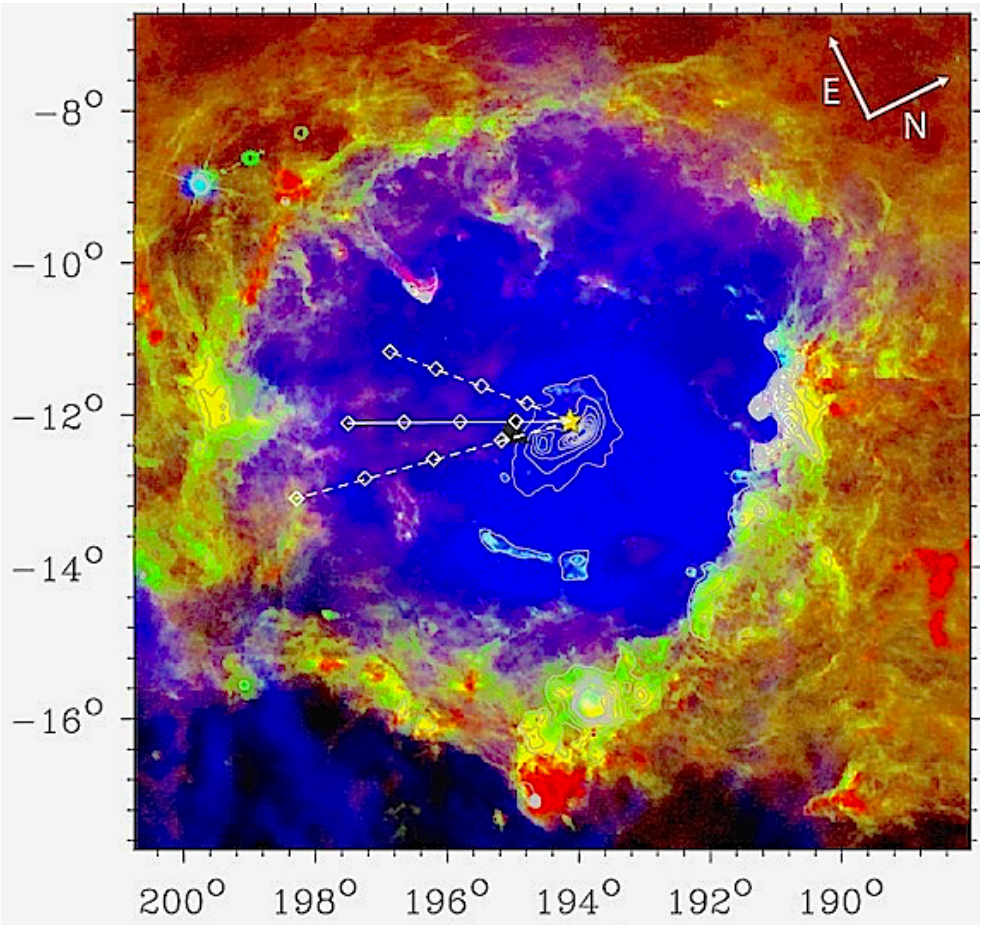
The line-of-sight (LOS) expansion of the Orion–Eridanus superbubble toward Earth is ~15 km s^{-1}, determined from line splitting of Hα. The total ionised gas component of the OB1 system is ~8 x 10^4 $M_{\odot}$. The aggregate kinetic energy of the OB1 is 3.7 x 10^{51} erg, which is about twice the total energy released during a supernova explosion (1.2–1.7 x 10^{51} erg). Kinetic energy (in this instance the momentum energy of all the gas particles within the system) is only one component of an ambient energy field. The total electromagnetic radiation comprising all the bandwidths from radio to gamma generated by all the physical reactions within the system adds up to a significant fraction of the total system energy budget. For example, soft X-rays emanate from the 10^6 K plasma in the interior of the superbubble, and this is only one small portion of the entire EM spectrum.

Barnard's Loop is a complete bubble structure all its own, nested within the Orion–Eridanus superbubble. BL sweeps up the mass of any preexisting superbubble matter as it passes through. Altogether, BL, the λ Ori region (surrounding Orion's head), and a few smaller-scale bubbles, are all nested within the Orion–Eridanus superbubble.



Source: Ochsendorf 2015 http://iopscience.iop.org/article/10.1088/0004-637X/808/2/111/meta

In this schematic of the entire Eridanus and Orion superbubble system,Hα gas structures are shown in blue contours. Dust structures are plotted in red. Solid lines trace faint filamentary structures. The Orion '*Hunter*' stars are plotted as black diamonds to show the immense size of the overall OB-energised region. Different subgroups of Orion OB of spectral type B2 or earlier are in different grey symbols. *Source: Ochsendorf et al. 2015 Fig 1d.*



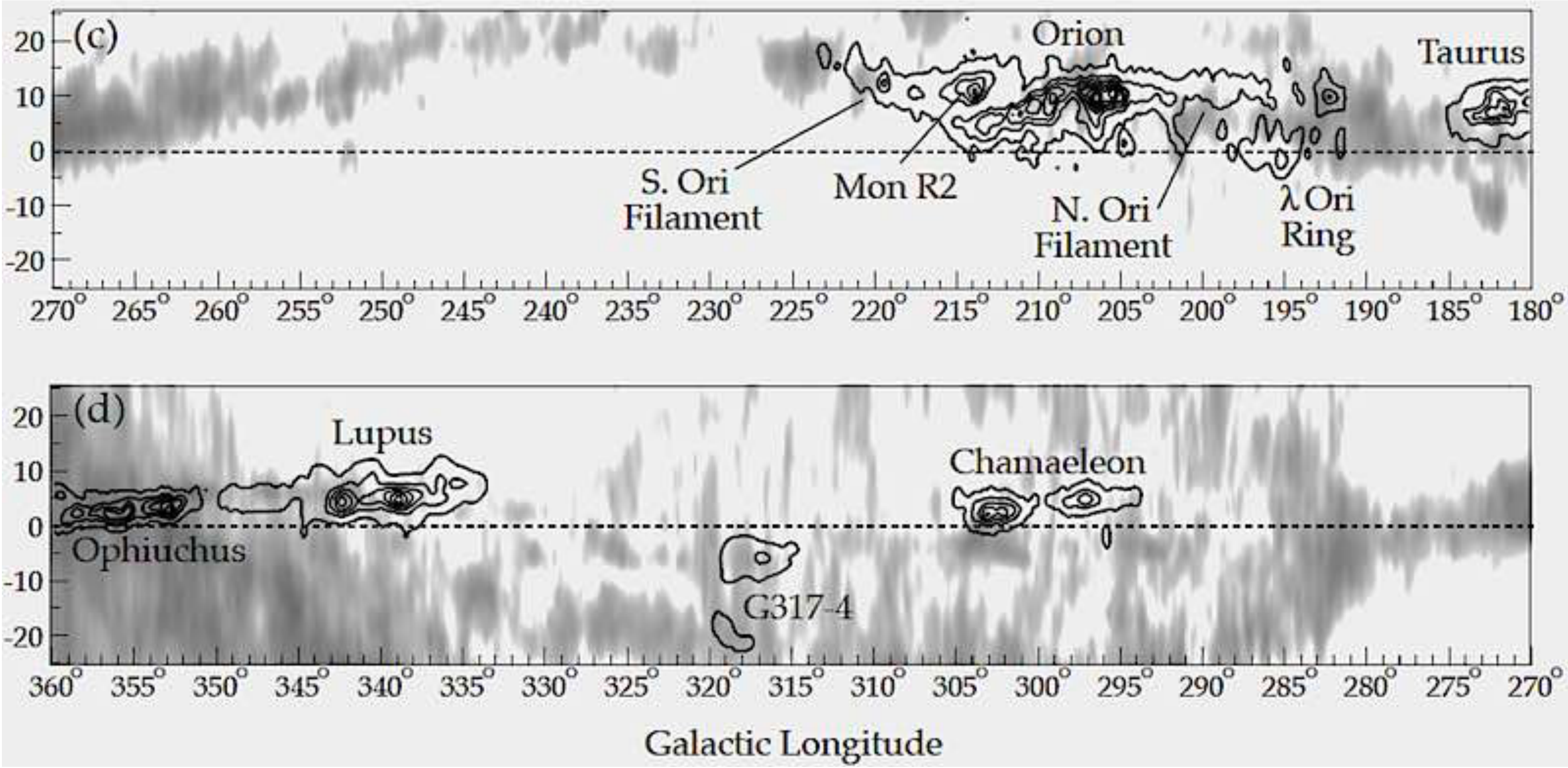
Three-colour image of the λ Ori bubble. The colour codes are the same as in Figure 1a. Overlain are contours of *IRAS* 60 μm. The solid line marks the trajectory of the star λ Ori starting 4 Myr given its current space motion. Open diamonds mark intervals of 1 Myr. The dashed lines are possible space motion errors in proper motion and distance. *Source: Ochsendorf et al. 2015 Fig 5*.

The symmetric HII region surrounding λ Ori has been known for a long time. About 1 Myr ago, a supernova injected a rapidly expanding shell into the parent molecular cloud (outside the bright circular emission ring. The SN shell expanded into the HII bubble to the right. The expansion velocity of the HII region is traced by observations of the dense molecular shell surrounding the ionised gas (blue) in the middle.

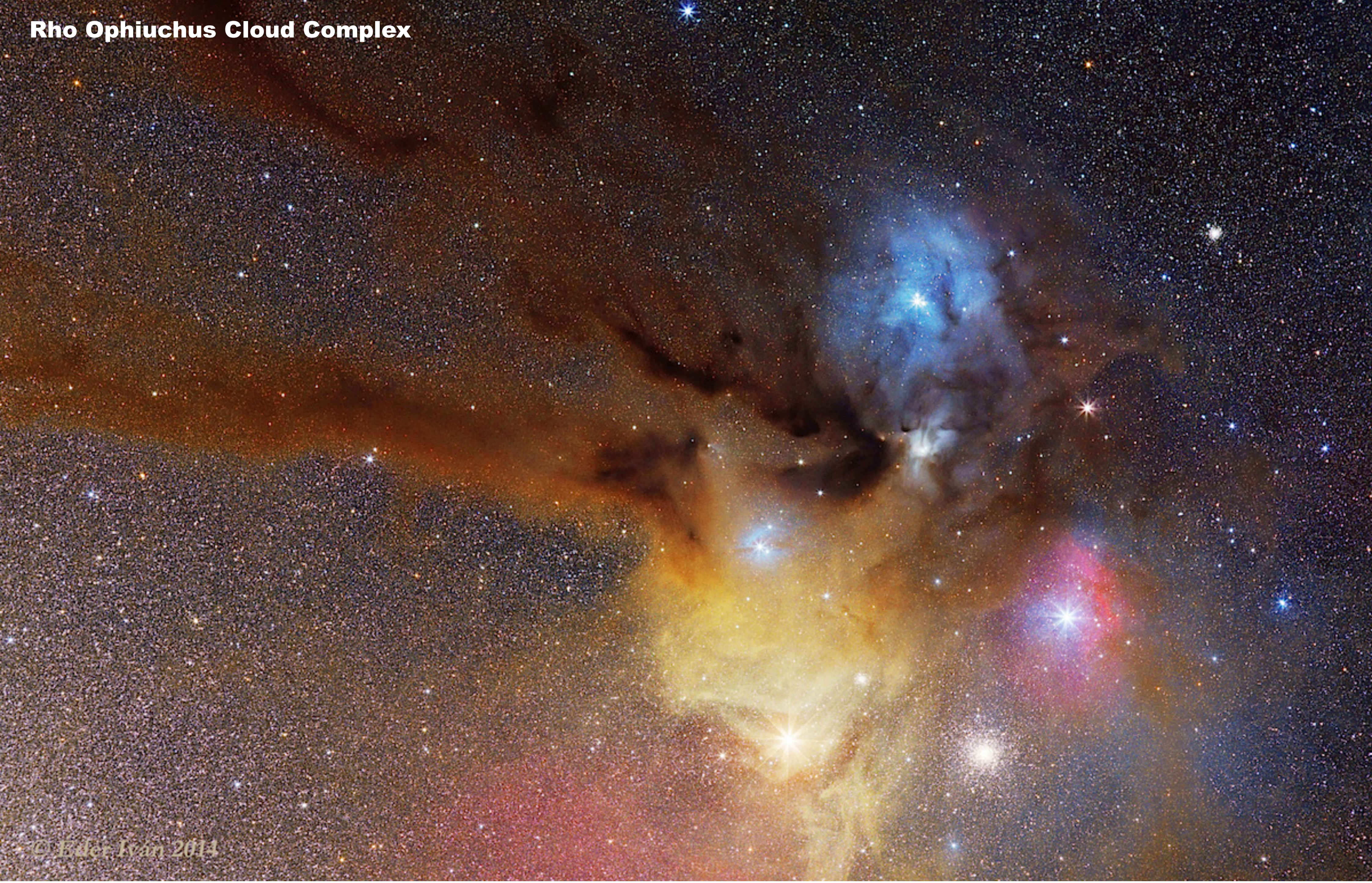
The Orion superbubble region has seen many SN explosion creating bubbles like this one. When the surface shock fronts begin to interact with each other, several types of structures result. The λ Ori bubble to the right is the simplest type of bubble, a spherical shell. The shell contains not merely the old SN's ejected gas. The expanding shock front sweeps up and compresses all the gasses and dust in front of it; this both pressurises and diversifies the chemical make-up of the gas.

When multiple bubbles intersect, their dense, rich shock fronts are fertile ground for new star cluster formation. The life cycle from new, clusters forming until they produce their own shock bubbles can be 5 to 10 Myr. The OMC will power the expansion and evolution of the Orion–Eridanus superbubble for another 20–30 Myr. Eventually the superbubbles will be depleted of further energy and run out of steam. The superbubble will disappear and merge with the surrounding ISM.

We see the spectacular and beautiful results every time we look at the Orion Nebula, the Heart and Soul Nebulae, or the Eta Carinae complex (the richest such assemblage in the Galaxy). Outside our galaxy we see the same superbubble-driven massive cluster-formation events in 30 Doradus (Tarantula Nebula), NGC 604 in the M33 Triangulum Galaxy, IC 1613's tri-bubble collect-and-collapse rings, and many many others. It's a safe bet that any bright region in a spiral galaxy that is rich with bright stars and red HII zones is one or more superbubbles at work. The long-term effect is a gradual consumption of a galaxy's star-forming gas reservoir. The inflow of pristine hydrogen along cosmic filaments can provide only about 15% of a MW type spiral's gas needs. The term 'red and dead' is very real future for galaxies.



A large fraction of the interstellar gas in a spiral galaxy such as ours is molecular hydrogen, and much of that is contained in the giant molecular clouds (GMCs) with masses of $10^4 – 10^6\ M_{\odot}$ and 50–200 pc in size. The simple, stable carbon monoxide CO molecule has played an essential role in the study of GMCs and molecular gas in space generally. HII does not have a permanent electric dipole moment, rendering it very difficult to observe in the cold interstellar regions where molecules form. But molecular clouds also emit CO spectral lines, which are easily observed. The molecular CO J=1–0 transition line (energy emitted in eV electron volts) at 115 GHz, has become the GMC's molecular analog to the 21-cm line of atomic hydrogen. Carbon monoxide surveys play a crucial role in many studies of star formation and galactic structure. Radio continuum, infrared, and optical observations of HII regions, OB associations, and other Population I objects, show that nearly all star formation occurs in molecular clouds. High resolution CO observations of dense cloud cores and molecular outflows have contributed the most to our understanding of how stars form. The contours above are spaced at 3.5 K deg, starting at 0.35 K. *Source*: Dame & Hartman, 2000.



Rho Ophiuchus molecular cloud complex, incl. Antares, M4, NGC 6144, M80, and the triple Rho Oph itself. This image has been processed in a way that gives is a 3-D feel, notably with the dust streamer entering from centre left. Credit: *Iván Éder*, *AstroEder.com*. Image captured at *Hakos Farm, Namibia* using home-modified Canon EF 2.8/200mm @ f/4, 23 x 2.5 min @ ISO 1600.

Rho Oph is the youngest and closest star-forming region to us. The 2MASS catalog lists over 300 association members. The young stellar objects inside the star-birthing cores of the Lynds 1688 (L.1688) have a median age of 0.3 Myr. At 100,000 to 1 million years, L.1688 is a rumbustious youth compared with the multimillion year old cluster-rich, gas-pummeled, high-mass cores in the Orion Molecular Cloud. By compare, the 30 Doradus Tarantula Nebula is a retirement community.

The ρ Oph cloud complex has been intensely studied since the early X-ray and IR space observatories revealed how young and active some of its cores are. The dense gas–dust core of Lynds 1688 in the r. centre of the image on the previous page has an exceptional gas / dust proportion for a molecular cloud complex — gas column densities of A_V 50–100 mag have been measured in the deep infrared, which is usually little affected by dust. ρ Oph is the nearest star-forming regions to us. At a declination of –23° to –28° it can be observed at +25° sky elevations from the mid-latitudes of both hemispheres. Its proximity makes even the low luminosity substellar objects in the region accessible to spectroscopy. The complex is an astro-imager's delight — colourful, detailed, comely, contrasty, both bright and faint enough for multiply stacked images to show their best.

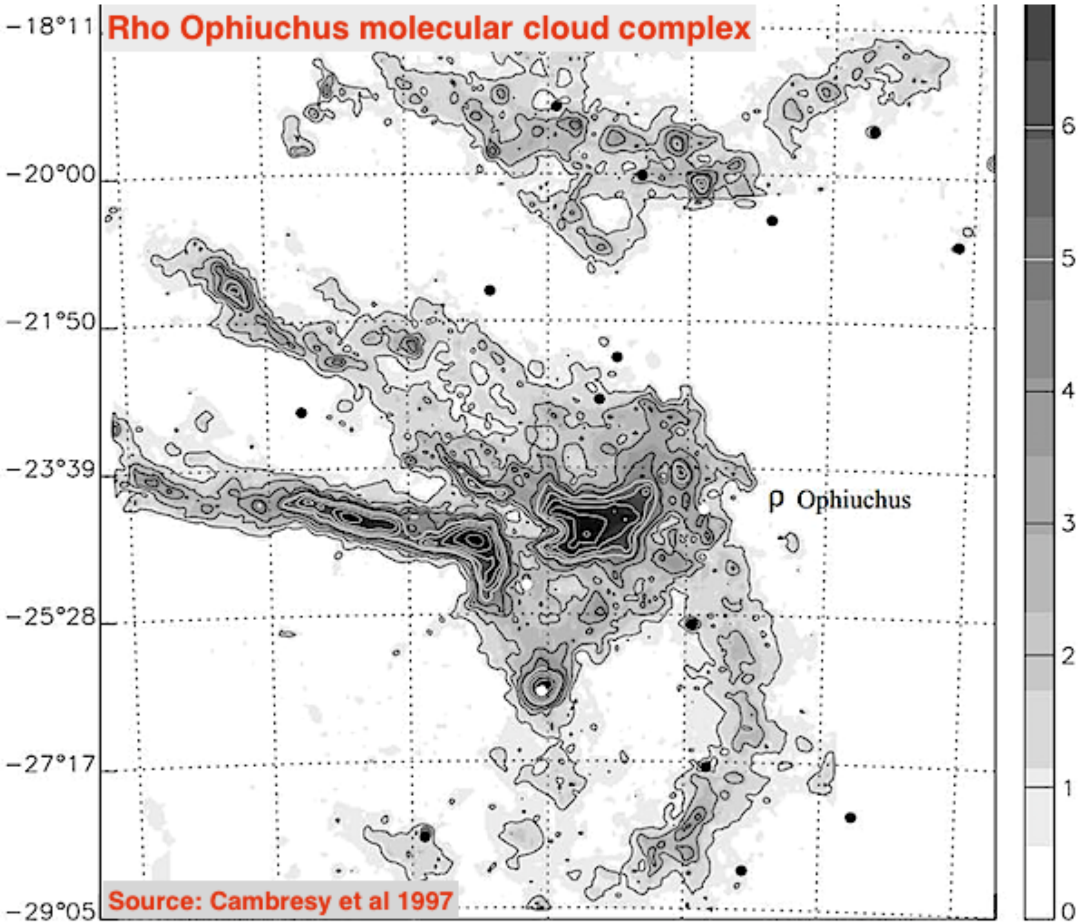
The sophisticated wide-field imaging and narrow-band spectroscopy data acquisition brought to bear on ρ Oph is impressive: ROSAT, Chandra, XMM-Newton search for and identify the polar-jet and accretion-disc X-ray signatures of young stellar objects (YSOs). Ground-based near-infrared (NIR) camera surveys sample sources over a large area. The HST NICMOS deep near-infrared (NIR) imager, the earlier IRAS Infrared Space Observatory, and the Spitzer Space Telescope all have surveyed the warm dust that surrounds ρ Oph's YSOs. The millimetre-band telescopes at ALMA have made large scale surveys of ρ Oph's gas and dust composition.

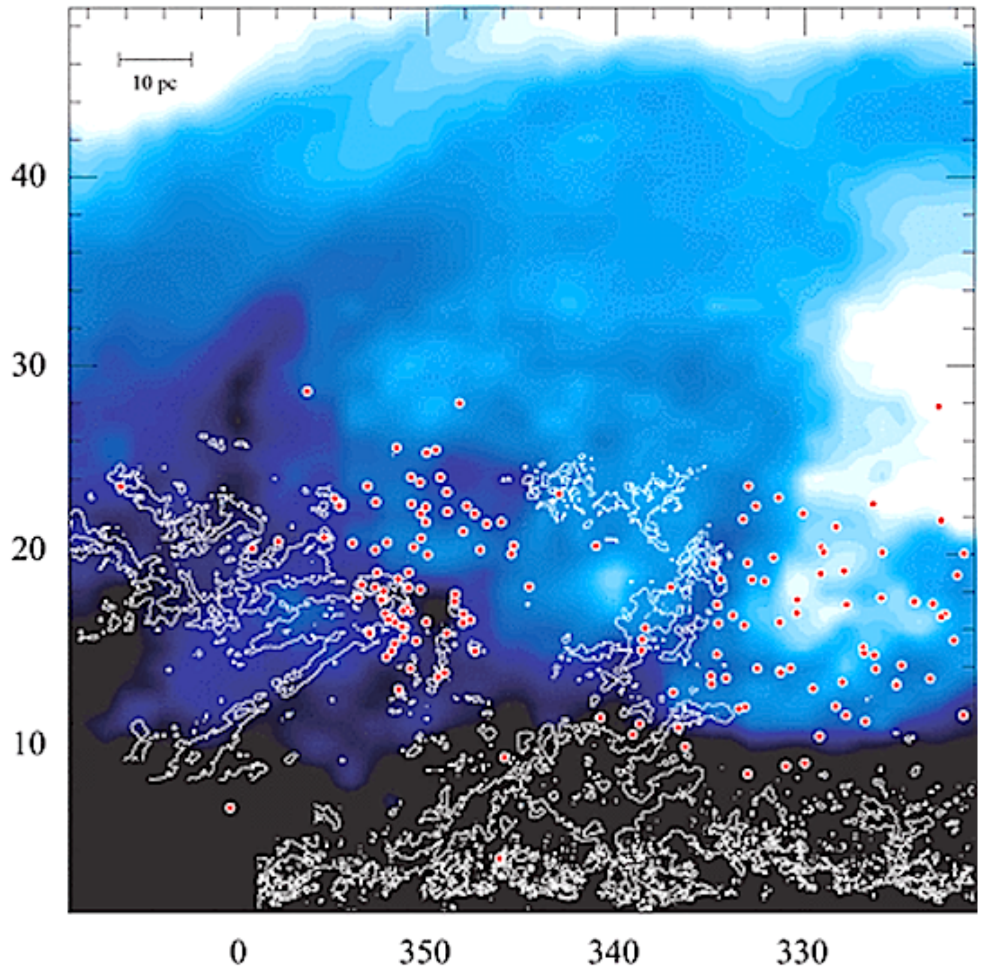
. The ρ Oph cloud covers approx. 4.5° × 6.5° on the celestial sphere. The dense star-forming cloud Lynds 1688 (centre l. on previous page) and two filaments L.1709 (above l.) and L.1755 (above r). These contain ~3,000 of HI, HII, and the simpler molecules such as CN, OH, and CO that are produced on dust particles in the cold molecular cores of dark clouds. ρ Oph contains a higher proportion of dust than many other molecular cores in the ρ Oph complex. Moreover, over 25 polycyclic aromatic hydrocarbons (PAH) have been identified. Their 3D distribution has not been fully established, but there appears to be stratification and fractionating activity in the clouds due to as yet undetermined chemical activity.

The ρ Oph complex's filamentary structures extend from 10 – 17.5 pc (32 – 57 ly) and can be as thinly striated as 0.24 pc (0.8 ly). Over half of that mass is concentrated around the L.1688 cloud, which is also the most active star-forming region. The bright compact objects centre l. are young stellar objects (YSOs) just now forming and still embedded in their natal gas. About 425 embedded infrared sources have been detected in and near the L1688 cloud. Of these, 16 are probable protostars, 123 are T Tauri stars with dense circumstellar disks, and 77 are weak T Tauri stars with thinner disks. ρ Oph's most-evolved stars range from 100,000 to a million years in age.

Magnetic fields in molecular clouds

The role magnetic fields play in molecular cloud contraction, collapse, and star-formation is crucial. Many amateur observers shy away from any sentence with the word 'magnetic' in it, assuming this to be one of astronomy's most conceptually and mathematically complicated. True, and yet not so true. This *2013 study by Hua-bai Li et al.* is the most readable yet comprehensive, summary of the subject seen by this author.





The active star-forming cloud of the ρ Oph cloud core is a well studied active cluster forming GMC notable for its peculiar filamentary streamers. Shock triggered star formation has been suggested by many authors. The three somewhat parallel horizontal features in the upper three bands suggests a morphology related to a supernova explosion that occurred in Upper-Sco OB Association 1.5 Myr ago. The blast completely dissipated the parent giant molecular cloud that formed the Upper-Sco. Evidence of a HI expanding shell has been detected,. The ρ Oph cloud is located right at the edge (image at right above) suggests that this shock wave also may have affected the Lupus clouds below and to the W. The SN shock wave would have terminated star formation in Lupus, but also would have triggered the present active star formation in the ρ Oph cloud. In the image on the right, the integrated intensity map of the HI emission is shown in blue. The ^{12}CO contours of the cloud boundaries and the OB stars (red dots) in Lupus, Centaurus, Ophiuchus, and a part of the galactic plane are shown. Note how much HI is available (in blue) for future generations of stars.

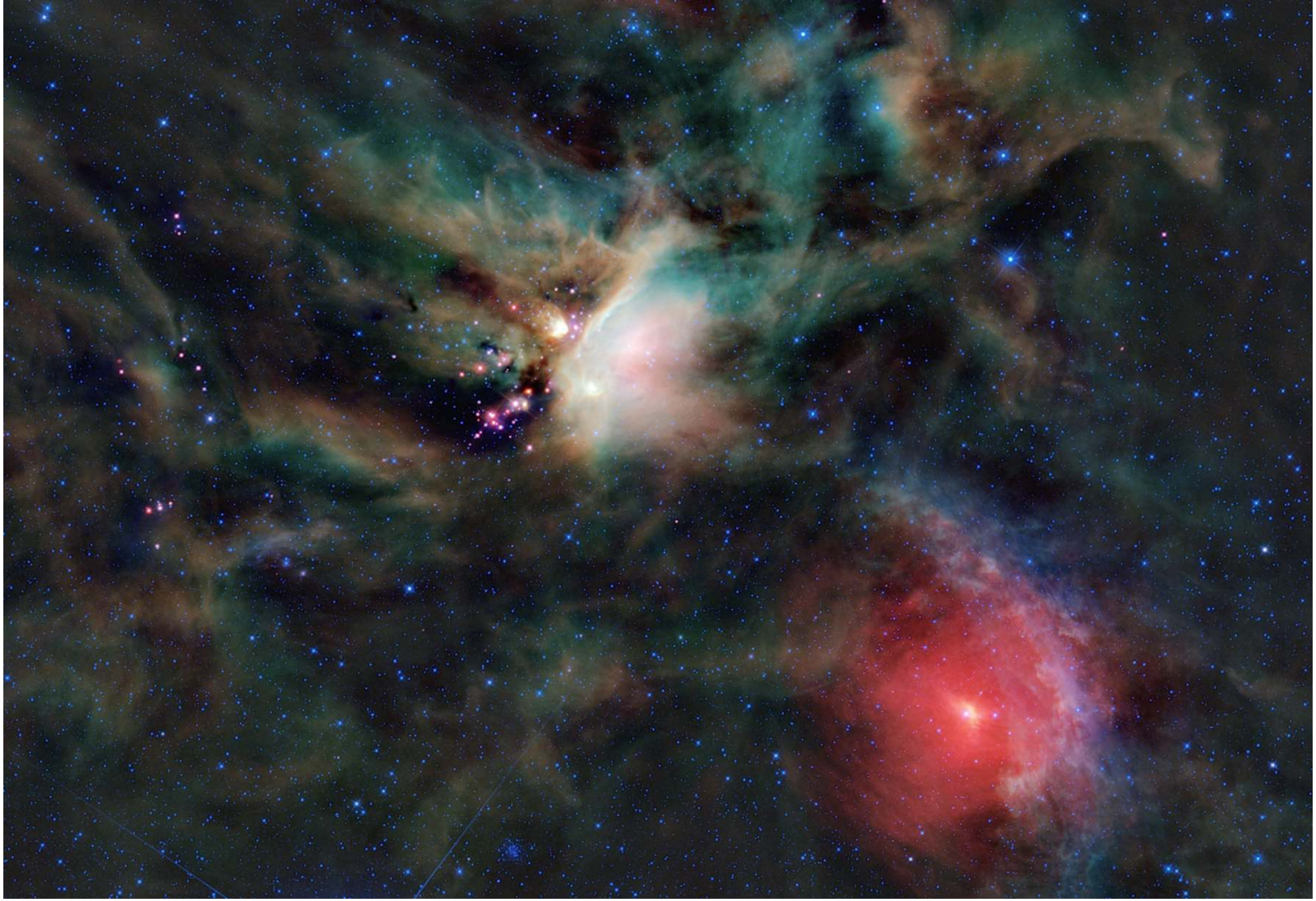
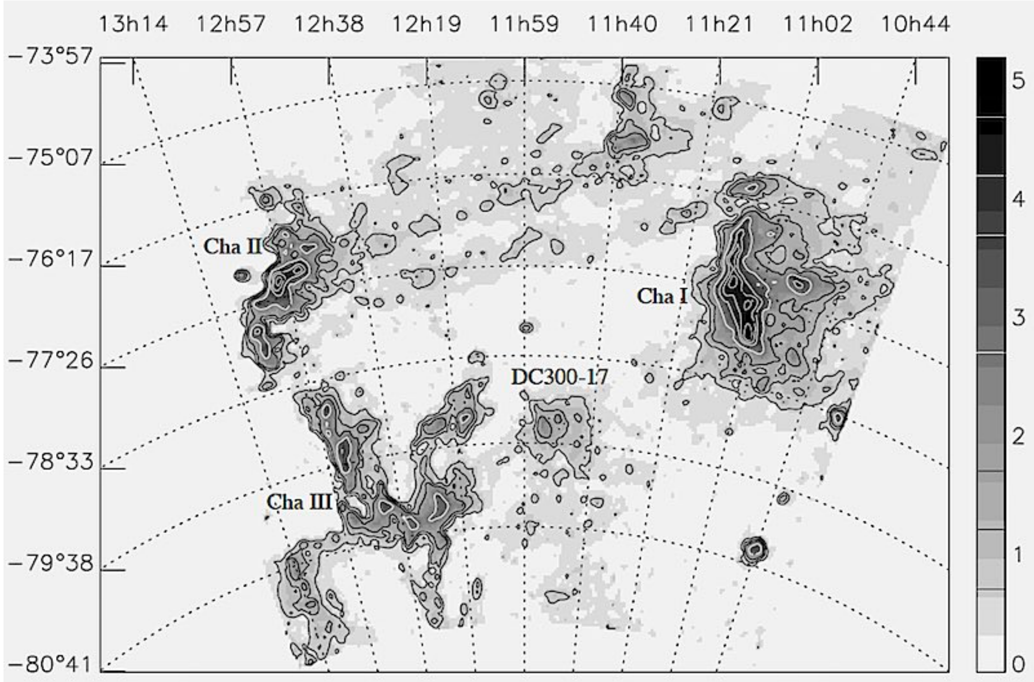


Image: *NASA/JPL-Caltech WISE* (*Wide-field Infrared Explorer*) Team

The L.1688 cloud was among the first regions imaged in X-rays by the 1980s era Einstein X-ray Observatory. In 1983 *Montmerle et al.* discovered 70 highly variable X-ray sources in a 2° × 4.5° field centred on L.1688. Since then hundreds of X-ray sources have been associated with Class I-III YSOs using ROSAT, ASCA, XMM, and Chandra satellites. Although YSOs emit less than 1% of their bolometric luminosity in the 0.1–10 keV soft X-ray band, X-ray surveys are a good way to identify cloud members because the X-ray-to-bolometric luminosity ratio is much higher than nearby field stars. The absorption cross sections of HI, He I and He II decrease rapidly with increasing energy; hence X-rays in the 2 –10 keV band can be detected through A_V = 75 mag of extinction. Most L.1688 YSOs have hard, time-variable X-ray spectra associated with thermal heating of magnetically confined plasma. The mechanisms that trigger flares and magnetic heating are not yet fully clear. *Imanishi et al. 2003* found that numerical models of X-ray flares on Class I – III YSOs in ρ Oph produced large magnetic loops with magnetic field strengths of 200–500 G (the Earth's is ~0.5 G). *Sources:* *Favata et al. 2005*; *Giardino et al. 2007*.

Chameleon I and II molecular cloud / star forming complex. *Credit: Gerald Wechselberger*.

Chamaeleon in the southern skies lies in an *extended Molecular Cloud* about 500 ly from Earth. This is a low-density, low mass region in which relatively few new stars are born. The brightest of which then illuminate their natal gas and surrounding dust. In the image to the left, in the l. centre is the bright blue Reflection Nebula IC 2631. Upper right of centre is the blue reflection nebula *Cederblad 111* (Ced 111); left above it is the pale yellow crescent-shaped nebula *Cederblad 110*. The arrow-like object below-left of Ced 111 is the infrared nebula GN 11.07.3.



Chameleon region extinction map from Cambresy 1999. All three of these clouds can be seen naked eye from very dark, LP-free southern skies.

Left: Part of Chameleon I star-forming molecular cloud. *Credit:* Iván Éder, AstroEder.com.

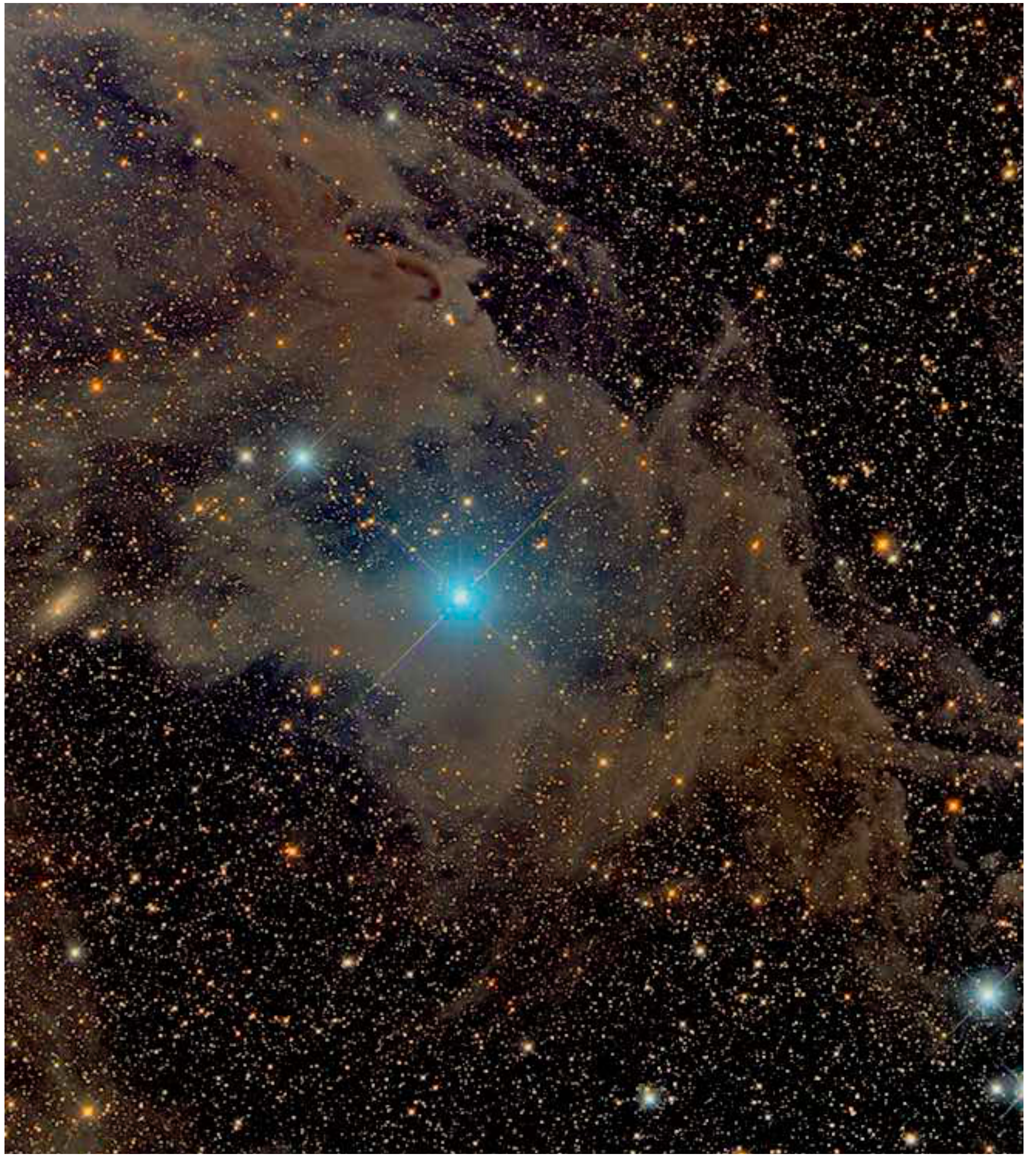
Chamaeleon dark clouds I and II are forming low-mass T Tauri stars. Chameleon III is quiescent. The complete cloud complex lies 400 to 600 light years from Earth and contains tens of thousands of solar masses of gas and dust. The most prominent cluster of T Tauri stars and young B-type stars are in the Chamaeleon I cloud, and are associated with the reflection nebula IC 2631. The two most-active star-forming cloud cores are Cederblad 110 (Ced 110) and Ced 111.

Ced 110 is a typical low-mass star forming core. Its new stars are affecting the collapse rate and contents of infant stars about to be born around them. Ced 110 contains nine low-mass stars crowded into a 0.2 pc region presently forming in evolutionary stages from Class 0 to Class II/III. Ladd et al. 2012 prepared N_2H+ $J=1\rightarrow0$ maps that identified an additional 13 ±3 $M_\odot$ of dense ($n \sim 10^5$ cm^{-3}) gas undergoing gravitational collapse. The molecular component of the gas outflow in the ^{12}CO $J=1\rightarrow0$ line shows a jet-like feature through the lower column density portions of the core.

The jet can be likened to a cometary head–tail object hurtling through its less-dense surroundings. A dust temperature gradient across the MMS–1 core is being gradually warmed by the nearby IRS 2 HII region (Cederblad 110). This region has produced several young stars in the recent past. Emission from the polar jets and accretion regions of the nine stars that formed first are now influencing the remaining dense gas in the region. Cederblad 110 is thus an example of the sequential character of small-cluster evolution, wherein already low-mass stars affect the future formation of even more modest-mass stars. Even when a star cluster originates in modest circumstances and thus produces modest results, the overall evolutionary pattern suggests that the first stars to form greatly influence what happens to the later ones. Even a tiny waterfall will cascade down into a pool and generate eddies,

Want to learn more? Here are some not too technical brush-up papers:

Williams, Blitz, & McKee, 1999
Bergin & Tafalla, 2007
Lada & Lada, 2003
Pelupessy & Portegies-Zwart, 2012



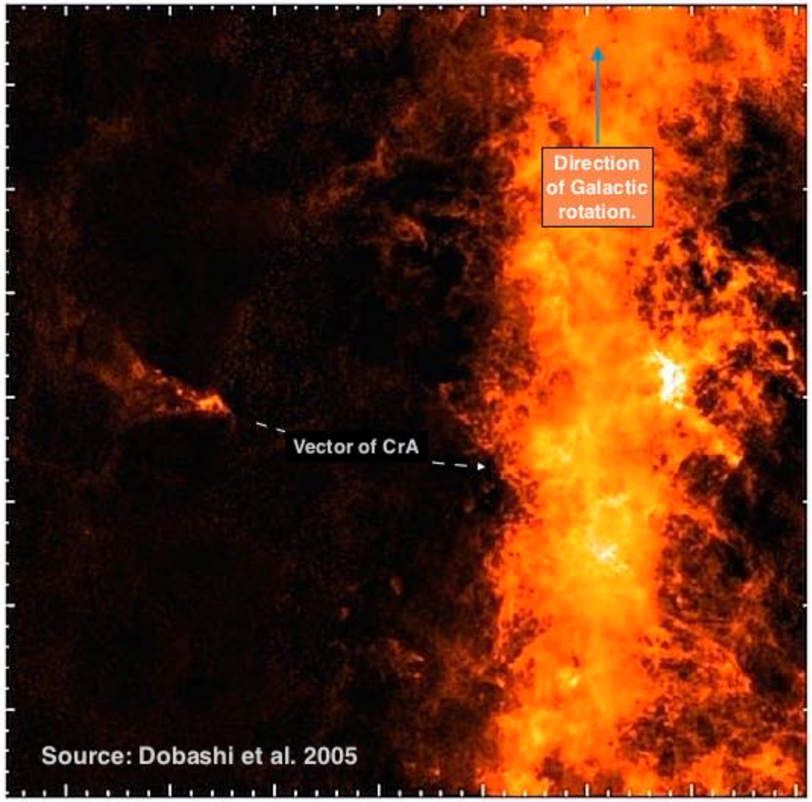
Part of the Chamaeleon III cloud. The small ellipsoid in left centre is the Local Group dwarf galaxy IC 3104. *Credit: Jose Joaquin Perez. Astrofotografia Austral*.

Corona Australis molecular cloud complex. The globular cluster NGC 6723 has shrewdly managed to avoid the clutches of reddening, delighting owners of ≥100mm refractors or ≥150mm reflectors who live southerly enough to see it. Visually it's like jumping from a fireworks show into a mud puddle.
Credit: Astrophotografía Australe by José Joaquin Pérez

The sword of Doom hangs by a thread above the Corona Australis molecular cloud (CrA). CrA has been widely surveyed at infrared wavelengths, in X-rays, and in the millimetre continuum. These reveal CrA to have highly variable extinction of up to A_V = ~45 mag at its core. In that core is a young cluster still so deeply embedded in its natal gas that the only radiation we receive on Earth is in the infrared. The infant cluster has been dubbed *Coronet*. There are now 55 known optically detected members, from the late B spectral type descending far into the low-mass stars, with two confirmed brown dwarf members and seven more candidates.

Detailed models of CrA's H_2CO radiative transport demonstrate that a rapid radial density gradient of $\varrho(R) \propto R^{-3/2}$ to R^{-2} describes drop from N_H 10^6 in the core to N_H 10^{-3} in the envelope. A decline in H_2CO abundance with increasing density suggests gas condensing onto dust grains. For the observed values of core radius and core mass (19 – 110 $M_\odot$), the velocity dispersion due to rotation or turbulence is too small to stabilise the cloud against gravitational collapse. The observed magnetic field strength also appears to be inadequate to prevent cloud contraction and eventual star formation. Put succinctly, the CrA cloud is in free fall even as its first protoclumps condense through pre-main sequence Herbig Ae/Be and T Tauri stars. *Source: Loren & Sandqvist 1983*.

CrA's stellar cycle began at the bottom of the cometary-shaped compression pressure well rather than the traditional spherical gravitational well. The pressure well therefore lies on minimum galactic gravitational potential but maximum gas pressure. This is favourable for dust freeze-out. Observed 1 – 3 μm emission confirms that dust grains are stratify by grain size with increasing depth into the

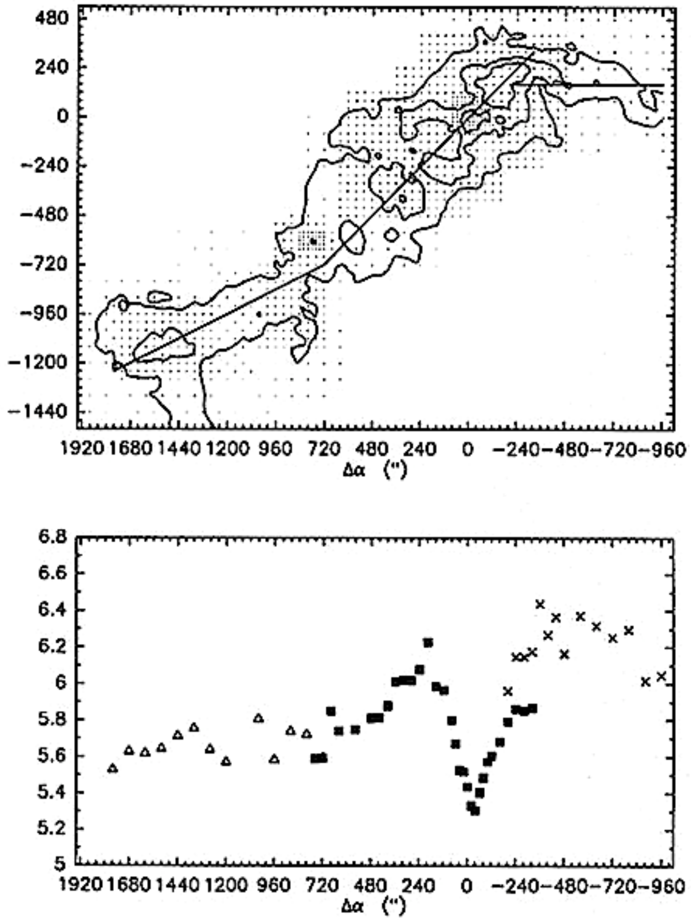


The CrA cloud lies ±130 pc (424 ly) beneath the Galactic disc. The cometary head-tail shape is characteristic of the second-stage in the evolution of a cosmic CHVC infalling from deep space through the Galactic halo *(Putman et al. 2002)*. As a cloud of this type encounters the denser gas nearing the thin disc, the shock dissipates the original cloud, but it's denser head continues at lower velocity. As its headwinds become more dense, the head deforms into a flat button shape. This initiates a compression cycle that will end in low-mass star cluster formation. The cluster's natal gas tail dissolves into the surroundings, as we see here. In CrA's case the gas loss is exacerbated by the pressure of the disc on the remaining gas, which will soon be consumed to the slight benefit of the Milky Way's gas reservoir. The amount is probably equivalent to the amount of calories we would gain by eating one peanut a week. *Text source: Forbrich 2008. Image source: Dobashi et al. 2005.*

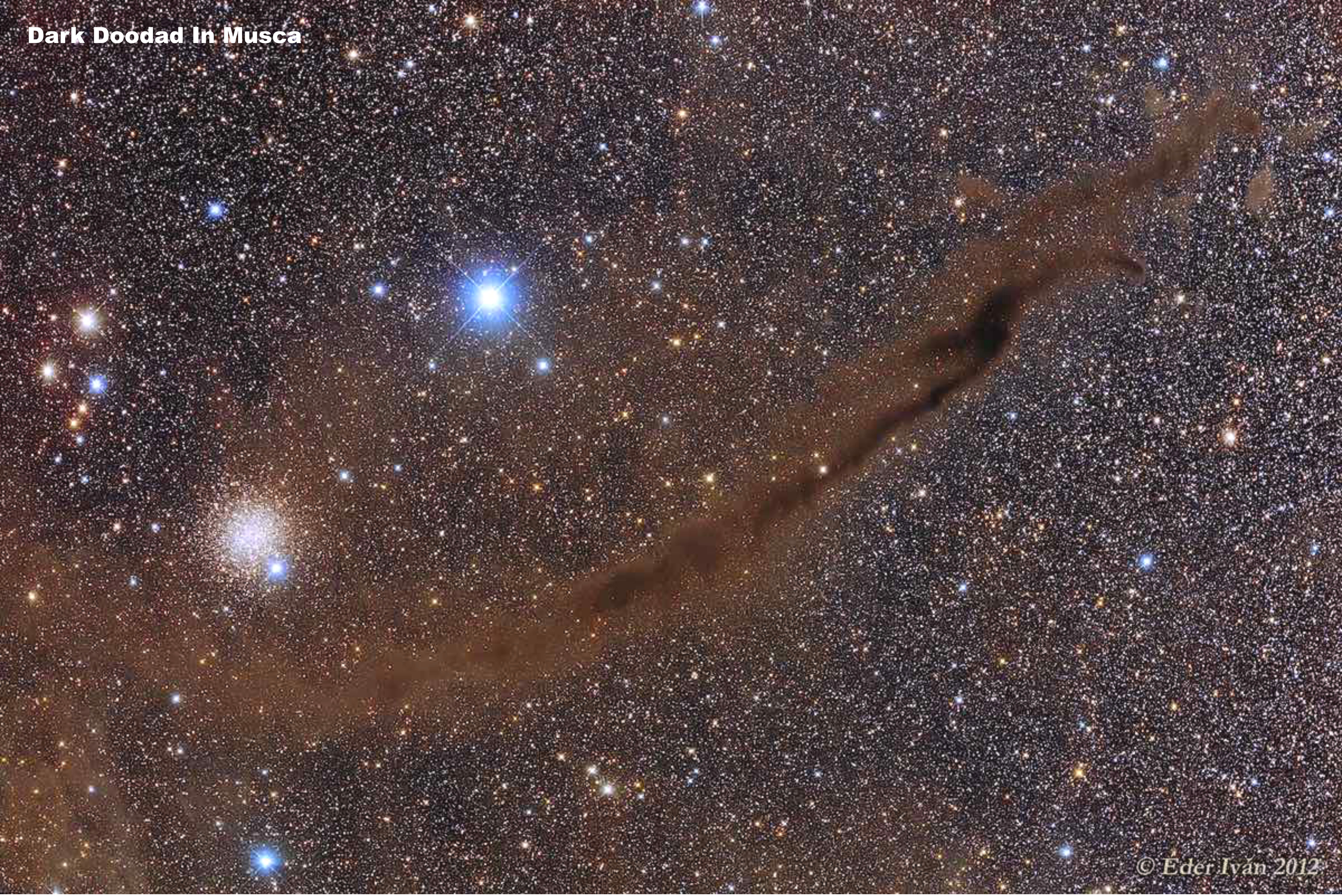
cloud because of the cloud's gravitational and magnetic fields. As can be seen in the figure to the right, dense clumps begin rotating as they shrink because of the tidal potential from the Galactic disc. The observed rotation and star formation rates of the cloud are consistent with the magnetic field strength implied by the grain alignment scales. Hence the general evolution of the CrA cloud is controlled by the ratio of its internal magnetic and gravitational potentials as they are affected by the Galactic magnetic and gravitational potential. *Source:* *Vrba et al 1981*

There is evidence that a gravitationally bound stellar subgroup is forming within the dense core of the molecular cloud. Photometry in the 1.6 – 20 μm bands reveal 2 $L_\odot$ sources near the core. Thirteen embedded sources are found within a 0.08 pc^2 area within the core. They exhibit a variety of evolutionary states whose bolometric luminosities range from 1 – 130 $L_\odot$. The most luminous sources are the B8 – A0 stars R CrA and TY CrA.

The estimated total mass for CrA's embedded cluster is ~19 solar masses, which implies a high star-formation efficiency of about 45% within this cloud. The overall gas use efficiency from the time the original gas mass entered the halo up to the protocluster stage today is 4%. The average efficiency of disc-shocked cluster formation in a molecular cloud rotating within the disc is about 5%. Surprisingly, a high-angle, high-velocity crash into a spiral galaxy is only slightly more ruinous to a molecular cloud that waiting inside the disc for the next spiral shock to arrive. Spiral galaxies are a poor career choice for a gas blob looking for a future. *Source:* *Wilking et al. 1986*.



Example of fractional rotation in CrA molecular core. This cloud is named Condensation A or *R CrA* for short. The line through the cloud density map at the top is the centroid along which velocity points were measured. The bottom image shows the actual velocities in km s^{-1}. The approx. planar line at 5.6 – 5.8 km s^{-1} is sharply interrupted at ~300 arcsec left of the zero point, rises to 6.2 km s^{-1} then swiftly drops to 5.3 km s^{-1}, rises again to 6.3 – 6.4 km s^{-1}, then returns to a new, slightly faster baseline at ~6.3 km s^{-1}. From our line of sight we do not know where the rotation's N and S poles point to, but with respect to us the cloud is rotating at half a kilometre per second towards us on the left and receding on the right. This indicates that the cloud is now undergoing gravitational free-fall into a rotating ball.



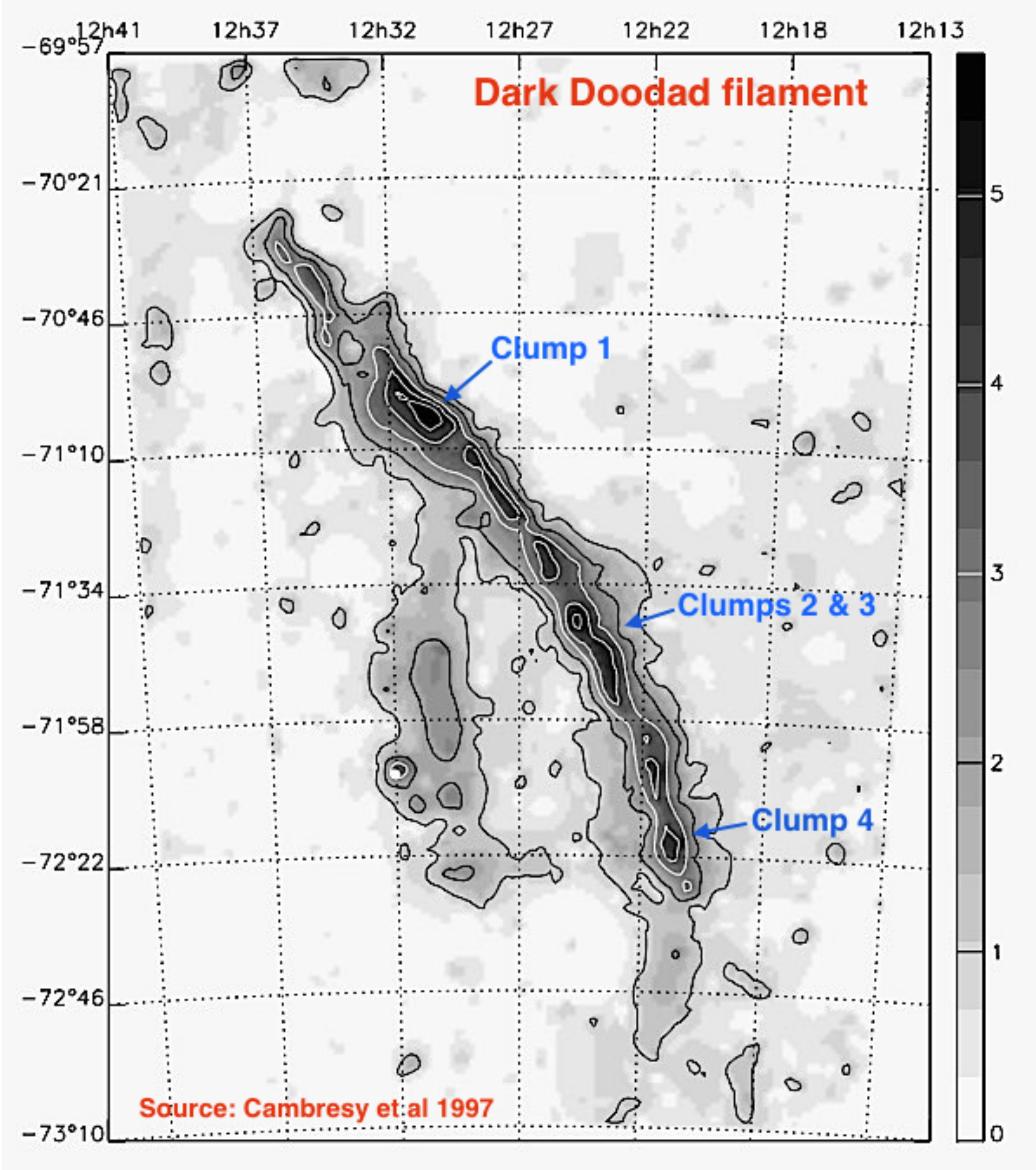
Dark Doodad in Musca. *Credit*: Éder Iván, astroeder.com.

Dark Doodad In Musca

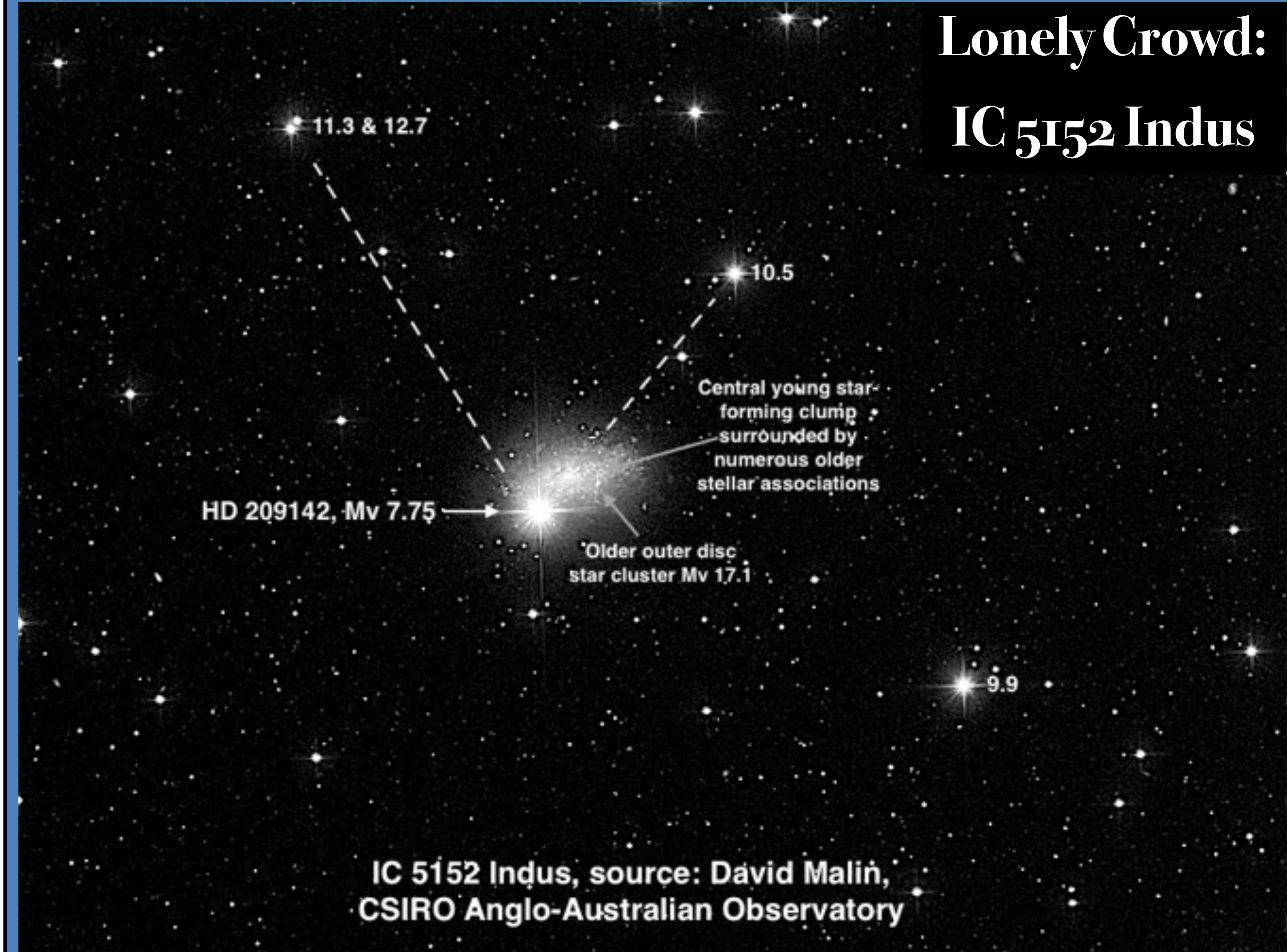
Rather officiously named *[DB2002b] G301.70-7.16 Dark Cloud (nebula)* on SIMBAD, the Dark Doodad easily qualifies for the Best-Known Least Known Object in the Sky. Bequeathed many names — Sandqvist 149, CG 21, BHR 80, TGU H1875, DCld 301.7-07.2, [DB2002b] G301.70-7.16, HMSTG436 — reported by *a great many observers*, *imaged by so many amateurs* that *a Google Images search* can clog your bandwidth for hours, try to find a professional paper that studies it in any meaningful detail.

Compared with the SIMBAD's Garden of Heavenly Delights results when querying any of the earlier objects in this report, the Dark Doodad brings up a pathetic eight citations under the IAU moniker for the object, *[DB2002b] G301.70-7.16* — the *least number of citations* this writer has encountered for an object so popularly known and oft-commented. All of those citations are mere entries in catalogs of one type or another. NED does not respond to *any* of the above query terms. Picky-picky. The *German Astrophysical Virtual; Observatory* (GAVO), which is the astro-researcher's first resort if SIMBAD comes up empty-handed, has the largest selectable *database of databases* one can find. Try to find the Dark Doodad on it.

The Dark Doodad is 3° long and has an aspect ratio of 20:1 at its widest. Surprisingly even given than slenderness, it is visible naked eye from a mid-latitude southern dark site. The site has to be totally LP free, though. This writer has seen it so many times that it is a test object with which to gauge how worthwhile the faint-fainty hunting will be. A brief *thread on IceInSpace* records several other visual sightings of it. But even if it is visible, that still doesn't tell us what it is.



Lonely Crowd: IC 5152 Indus



IC 5152 Indus is the archetypal galactic fly on the wall. It is a dIrr dwarf irregular galaxy 2.156 Mpc from Earth. It was discovered by DeLisle Stewart in 1908. The Indus Dwarf's far-off 7.02 million ly (Mly) wisp in the eyepiece is surprisingly easy to spot given its remoteness. Like nearby Barnard's Galaxy and IC 1613, it is in the middle of a starburst episode that mostly takes place around the edges. That seems odd given that IC 5152 is a featherweight galaxy of XX solar masses that lies 2.15 Mpc from the Milky Way, just outside the gravitational zero velocity surface of the Local Group. It is not a part of any of the other galaxy groups in the thin pancake of the Local Sheet some 30 megaparsec in diameter.

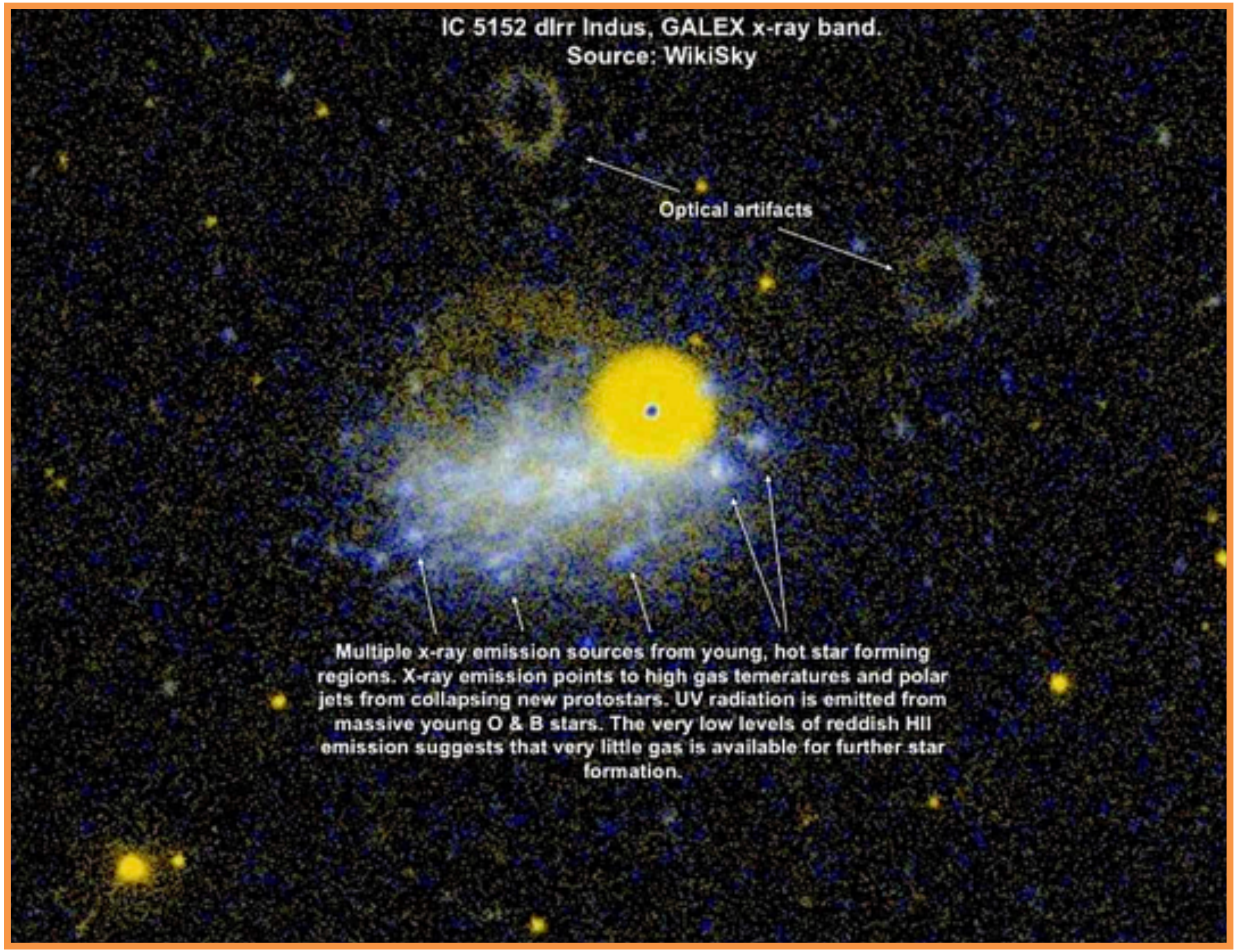
Being so southerly, IC 5152 is seldom visited, and a bit of a trickster when you try. It's tucked up right next to mag 7.7 *HD 209142*, though the galaxy itself is M_V 10.9 and spreads across a rhomboid-shaped 5.2 x 3.2 arcmin surface. The trick to spotting it is to pan the stars in the field using averted vision and look for the star with a cometary flare. At 80x in a 100° eyepiece there are three field stars in that magnitude range in a near-isosceles triangle. The star with the white beard should be the long-vertex one if you've got the right triangle. The galaxy shows easily in a 6-inch at 164x. An 8-inch at 212x reveals an obvious squashed rhomboid shape with feathery edges and a bright but featureless core.

The Indus Dwarf (Indus for short) is the anonymous face in the crowd in the sports arena of every galaxy group. It is there because it's part of the crowd that's been there since the beginning. It is so ordinary, sitting way out there in the cheap seats all by itself, that few even notice it, much less look at its features. It isn't much interested in the scrummy hubbub in the middle, doesn't get excited at every clashing play, and only every once in awhile makes a polite chuckle to add its $0.02 to the synergy that gives the players and onlookers of every galaxy match its thrill. At those moments it wakes up, waves a bit, then dozes back into somnolence.

Sociologists are fascinated with the face-in-the-crowd personality: they are the fly on the wall of social evolution. They watch in a quiet chair off in a corner as cocktail parties transition from an exciting, noisy melee of everyone mixing and talking at the start, then observe the slow ebb of crowd noise as small groups move off to carry on conversations of their own, and finally dwindle on down to couples carrying on fitful conversations and singles paying more attention to the books on the table or art on the walls. The flies on the wall have seen everything, they know the crowd. They have stories to tell that end up being much larger than themselves. The difficulty is getting them to talk.

Dwarf irregular galaxies in isolated locations tend to be gas-rich. This is a legacy of the galaxy's ancient origin, in which only a fraction of its natal gas was used up in star formation. Once the early stars were blazing brightly within the first million or so years of the galaxy's life, their UV radiation dispersed the clumpy and filamentary streams of leftover gas to an uneven but thin soup too rarefied to self-gravitate without some external injection of energy. The 1st generation supernovae blew considerable amounts of metals-enriched gas into the galaxy, some of which escaped. Most of it went high into the galaxy's gas halo but eventually gravitated back to the core region. (A handy rule of thumb for SN ejecta return from a SN in a dwarf is 250-500 Myr.)

Today IC 5152 glows only weakly in the IRAS IR band, which means the galaxy's internal gas is not much warmed by the radiation of the



stars, which in turn implies an ambient internal energy median of <12.8 eV. It is quiescent in Ha and X-ray, but is quite bright and richly detailed in UV (see Fig 2 below); indeed the UV emission follows the V band in physical size but is peppered with at least 28 very bright emission spots. These are recent O and B star forming hot spots, meaning that the galaxy has interacted with one or more gas clouds at least as massive as $10^6\ M_{\odot}$.

Zijlstra et al 1999 showed that Indus has a young population of stars about 10 million years old, and and a somewhat older population of 68 to 100 million years old. These are typical configurations of a galaxy that has interacted with a very massive 106 to 107 cosmic high-velocity cloud (CHVC) or groups of clouds. The shock front from the initial interaction spawned a burst of massive star formation, perhaps 4,000 to 10,000 stars. A shock wave propagates irregularly off uneven densities of gas and is perturbed from within by its own turbulence. Multiple clusters form in a rather brief time (10^5 to 10^6 years). The first massive O star supernovae commence around four million years; a first-round supernova cycle in a gas-rich cluster can last 25 million years or more. A rapid succession of shock fronts compresses the galaxy's remaining gas into a second round of star formation.

We can see this in snapshot form every time we look at the R136 cluster in 30 Doradus (the Tarantula Nebula) or NGC 604 in M33. Even in a scope as modest as my 8-inch I can see the bubble being evacuated around R136 by its UV radiation. That bubble sets the conditions for the second-stage star cycle. When the first-round supernovae start popping, their high-velocity shock waves will catch up to the slow-moving UV fronts, and the turbulent melee will look like a rugby scrum tossed into the sky. Every time we look at the CMD of a globular cluster we see the end result of a two-stage star formation episode. [Except Ruprecht 106; see the article in this *Nightfall*.]

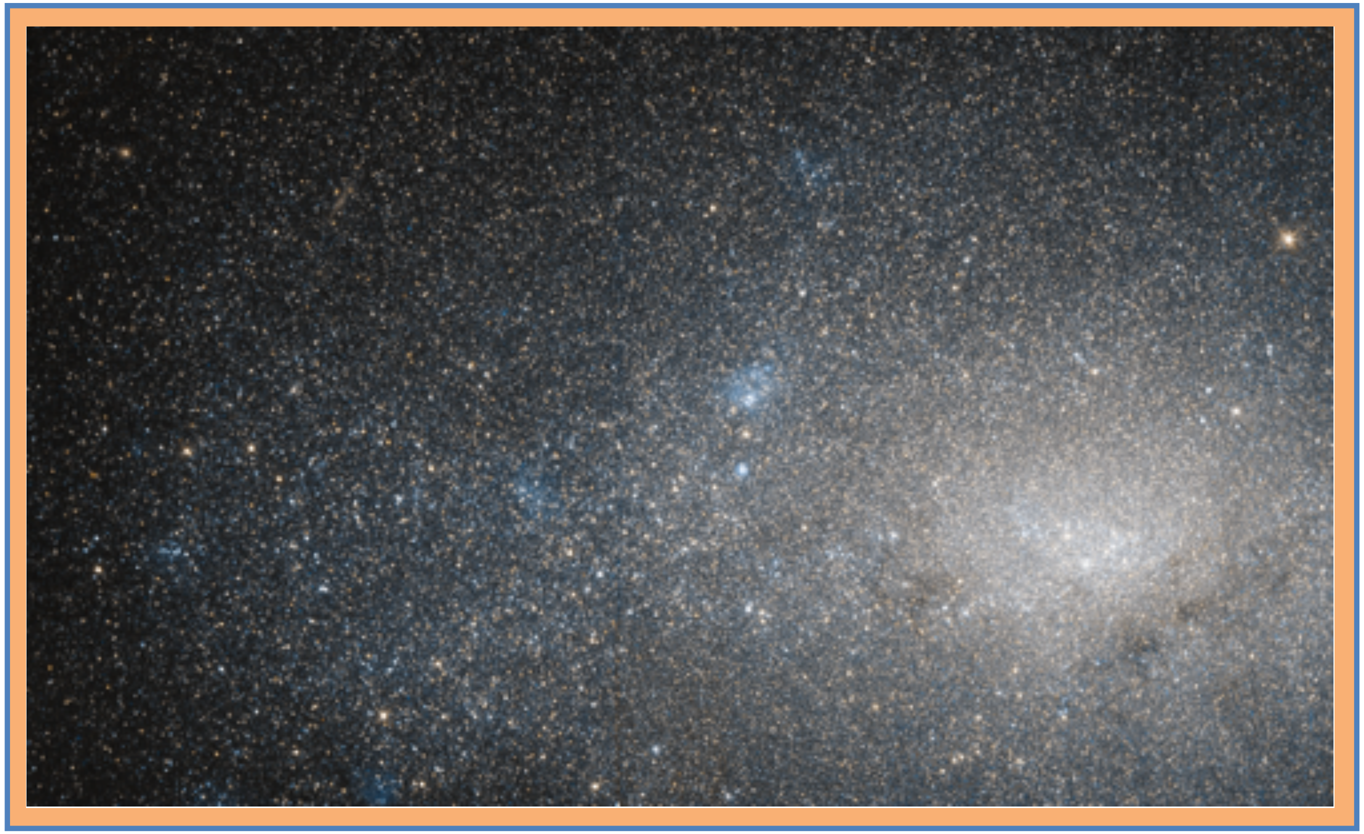
Indus and Pavo from Johannes Beyer's 1603 Augsburg *Uranometria*.

Most isolated dwarfs evidence this same episodic star formation pattern. IC 1613 was a dwarf with a large spheroidal core mass for billions of years until it interacted with three massive gas clouds in close succession between 30 and 50 million years ago. The interaction was >1 kpc off to the side, giving the galaxy its present dIrr dwarf irregular status. WLM in Cetus interacted with a gas cloud which triggered a spectacular series of star forming regions very close to the galaxy's core – so close they can be seen only in very large telescopes imaging in the XX band. Where do they get all that gas, and why so episodically?

Intergalactic space, especially inside galaxy clusters, is known to harbour large numbers of CHVCs, or compact high-velocity clouds. These are leftover atomic hydrogen overdensities that have existed since dark matter and normal (baryonic) matter first began to interact and collapse into clumps, but never grew large enough to self-gravitate into compact objects. Intergalactic CHVCs are only lightly bound. They are purely atomic, meaning they have no HII molecular hydrogen. HII forms only with difficulty in the extraordinary tenuity of space. A large number of hydrogen atoms need to gather together close enough for the HI-to-HII reaction to set in. Cosmic dust is just the ticket: tiny, cold, and sticky. Dust particles are cosmic catalysts. HI atoms accrue in sufficient densities on dust particle surfaces to bond as HII, which they cannot do as free particles in intergalactic space. Dust, in turn, forms mainly from the ejected surface gases of very old asymptotic giant branch (AGB) stars. The gigantic, cool surfaces of these stars contain significant carbon and oxygen abundances dredged up from the core, which is fusing helium into carbon and oxygen. The surface temperatures of AGB stars are cool enough that atoms can bond into molecules such as carbon monoxide (CO), cyanogen (CH), hydroxyl (HO) and even complex hydrocarbons like ammonia and formaldehyde.

We can see several star-forming regions in this HST image of Indus acquired in 2014. Some are in the centre and others on the outskirts. Indus's star forming clumps are mostly in the middle while young star clusters are in the outer regions. Some of the clusters are still embedded in their gas; others have ejected their gas. The galaxy is suffused with a faint red glow, a signature of HII having been formed on dust. Dwarf irregular galaxies have a large gas reserve spread all through. Large-scale perturbations from colliding with a gas cloud begin in the region of first contact. Compression shocks send shock waves through the galaxy. When a shock wave encounters a denser than normal gas pocket, star formation begins. Most dwarf spheroidal galaxies, on the other hand, have been tidally stripped of their gas by encounters with large spirals like the Milky Way. By now they have very little gas in them, so star formation from an CHVC collision initiates in the dense core.

There are at least five wispy bright patches in the NE quadrant of Indus's outer SW quadrant. The brightest emission patch shows an obvious star cluster still forming; two of the others appear to have slight stellar overdensities amid the faint glowing gas. The calculated mass for the most luminous red supergiants in these clusters is up to 50 M. Indus's nebular regions do not resemble the intense, bright pink



clumps of star forming clouds in spiral galaxies like our own. The original progenitor clouds were large but tenuous. Indus's star clusters are actually unbound stellar associations whose main star-forming activity occurred a hundred or more million years ago. By compare, the Pleiades is 106 million years old. The cluster in the upper centre of IC

5152 resembles what we might see if we were gazing upon our nearby Pleiades if we were gazing at IC 5152's distance.

More interesting from the evolutionary history perspective are the string of four dark patches just below the core to the SW and the single patch directly E of the core. From the amount of dimming (extinction) they produce but also the fact that plenty of stars can been seen on them, they lie somewhere in the middle halo of the galaxy, with Indus stars in front and on all sides.

IC 5152 has had a recent star-forming episode that appears to have begun several hundred million years ago and may be in its last stages of formation by now. Its modest contingent of hot young star clusters make it quite luminous for a small galaxy. It is just beyond the edge of the local galactic reach. The Local Group's zero-velocity surface (ZVS) where gravity and escape velocity balance is a wobbly bubble averaging 1.83 Mpc (5.96 Mly) from the barycentre of the Group. The barycentre lies somewhat near the centre point of a triangle made of the Milky Way, M31 Andromeda, and M33 Triangulum and the vertices. The ZVS is shaped like a pancake because of the modest gravitational contributions of all the dwarf galaxies in the Group. IC 5152 at 7.02 Mly (*Karachentsev 2004*) lies just outside the ZVS. IC 5152 is petite, only 2.6 by 1.3 arcmin (4160 x 2020 ly) and shaped like a badly thrown pizza. Surprisingly for a Local Group galaxy, IC 5152 features in very few papers, e.g. *Zijlstra 1999*; *Hidalgo-Gámez 2002*; *Lee, Grebel & Hodge 2003*; *Buyle 2006*.

Unlike spheroidal or elliptical dwarfs, the dwarf irregulars are somewhat clumpy. This is partly a fossil from when they were first made amid a large number of other clumps nearby, and partly a relic of previous star-forming episodes over the eons. The most recent episode

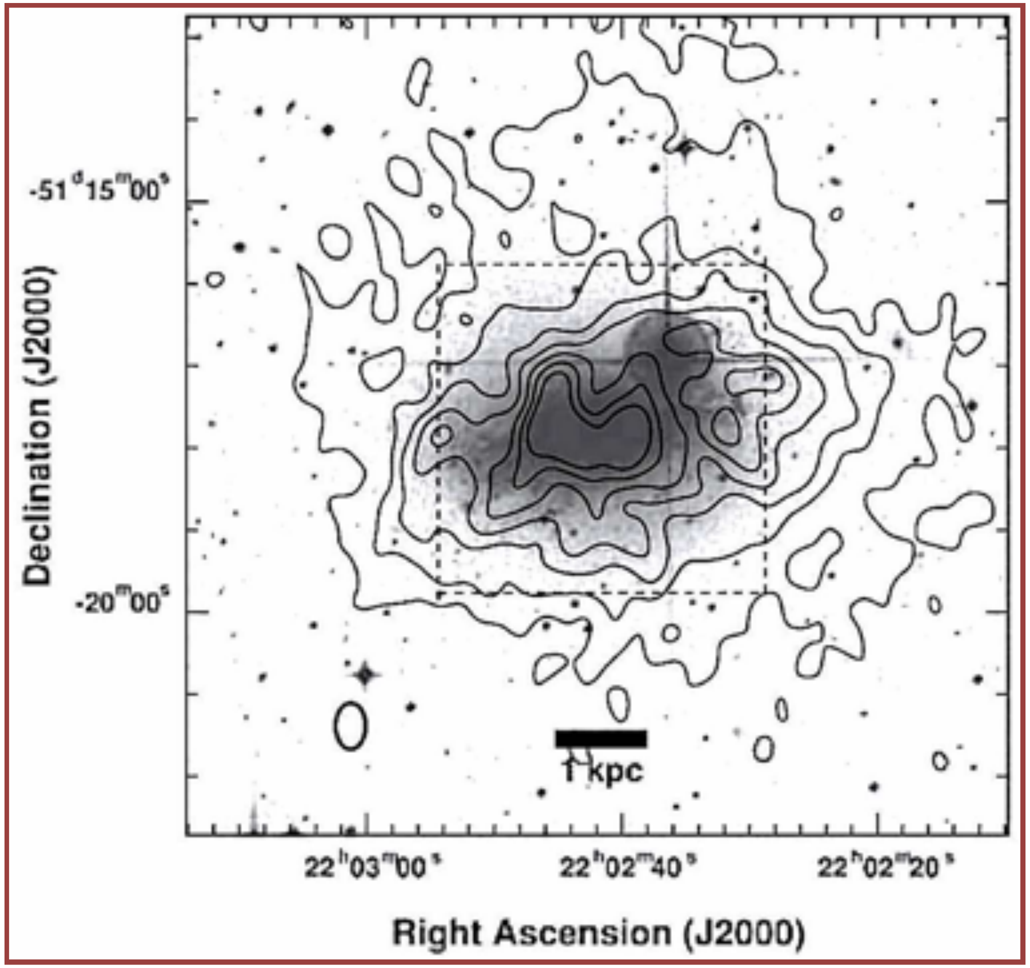


Fig. 1 from *Buyle 2007*. Indus's star formation isochrones (contours of equal age) roughly match its HII density isophotes (contours of equal luminosity, shown here as black lines). These contours, in turn, reveal the galaxy's baryonic mass distribution.

that we know about through spectroscopic evidence began about 10^8 (100 million) years ago and ended $10^{7.8}$ (63.1 Myr). The turbulent shocks and more complex atomic mix in the gas reserve, then underwent a second-stage round of star formation commencing 10 Myr ago. The clusters we see today are the remnants. Most dwarfs with a history of CHVC-induced starbursts survive only two rounds of star formation. By then so much gas has been used in stars or ejected by supernovae that the galaxy is finally left in peace . . . until the next giant atomic cloud comes along. The thick ellipse in the lower left is the beam coverage of the *Australian MOPRA mm-band radio telescope* used to assemble this map.

IC 5152's star-formation cycle is also its swan song. The original CHVC cloud has dwindled to a mere 67,000 M of HII. This suggests that the galaxy had in fact retained a core/halo of HII from its primordial formation perhaps 12 to 13 billion years ago. Today's late bloomer phase is its possibly a last-gasp starburst after having consumed most of its primordial hydrogen reserves in earlier bursts. Its metallicity [Fe/H] is –1. That implies multiple generations of starbirth in its history. By the time a metallicity reaches as high as –1 (from < –5 primordial) it is littered with informative [α/H] and [Ba/Eu] ratios from Type II SNe and [Fe/H] from SNe Type 1a. Today spectral energy distribution analysis has gotten so sensitive astronomers can tell us *Star X* has *y%* of titanium oxide, sodium/oxygen, or barium/europium, from how many stars of a particular kind they were, and when those stars blew up.

Having been so little studied, IC 5152's stellar formation history has not yet been satisfactorily determined. The supernovae and AGB envelope ejections of normal starburst evolution should have rid its centre of gas long ago, reminiscent of the supernova that opened up the Local Bubble of evacuated gas surrounding our Sun. We live in a felicitously located low-density gas pocket compared with the mass densities of the galaxy at large – the galactic analogy to our favourite dark-sky site far from urban light noise. NGC 5152, like WLM and UKS 2323-326 in Sculptor, conduct their star formation in the middle, while the remote dwarf irregulars such as Barnard's Galaxy wear their new stars like diadems on a tiara adorning the galaxy edges.

Here we have to end the quest. IC 5152's complete starform history hasn't yet been written. We don't have enough data yet. Maybe some bright young button in the PhD world will skip the neutrino-cooling-in-black-holes canapés that beguile the grad student forums these days and get back to that fly-on-the-wall sitting way out there in the cheap seats.

Australia's MOPRA dish can observe several spectral lines simultaneously between 16 and 116 GHz. The dish luckily escaped the disastrous 2013 bush fire that destroyed the historic Great Melbourne Telescope at Siding Springs, but the on-site control room station was severely damaged.

NGC 7789 Caroline's Rose open cluster, Cassiopeia

UKS 2323-326, Sculptor's Other Dwarf

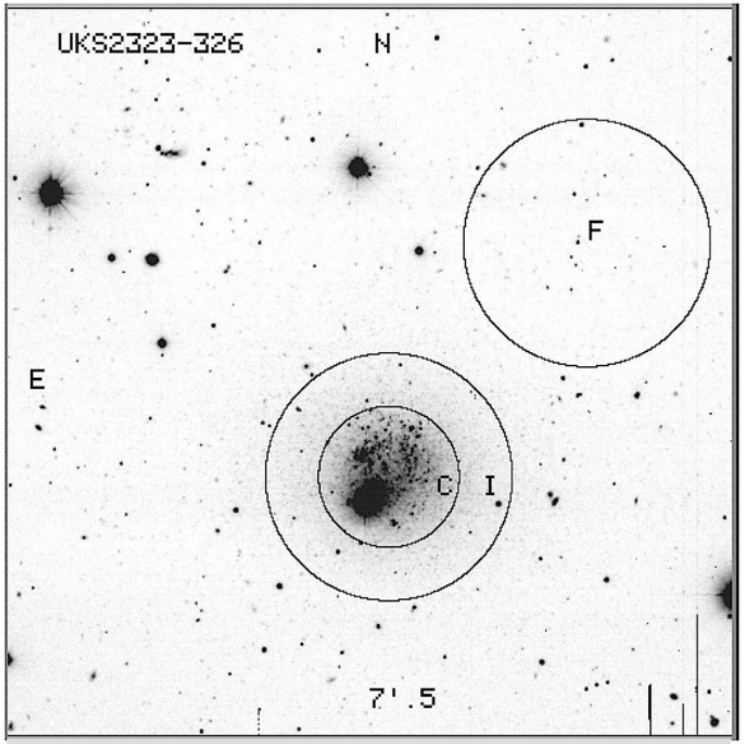
Dana De Zoysa

Why do dwarf galaxies have such inconsistent histories of star formation? Some, like Sculptor and Hercules, formed almost all their stars soon after the Reionisation Era and have snoozed through the rest of their *z*'s till today. (See more here: *1*, *2*, *3*, *4*, *5*).

Others, like Phoenix, Fornax, Carina; and the M31 satellites And II, III, XII, NGC 147, 185, and 205, add stars in bursts of new formation at irregular intervals — a counterpart to palaeontology's punctuated equilibrium theory — for which there is no single explanation and no system-wide correlation.

Still others make a proportion of their present populations very early on, age quietly for billions of years, then suddenly and inexplicably explode into life. IC 10, WLM, UKS 2323-326, Leo A, Pegasus, and the Sagittarius Dwarf (not to be confused with the presently disrupting Sagg Dwarf Irregular) are among these.

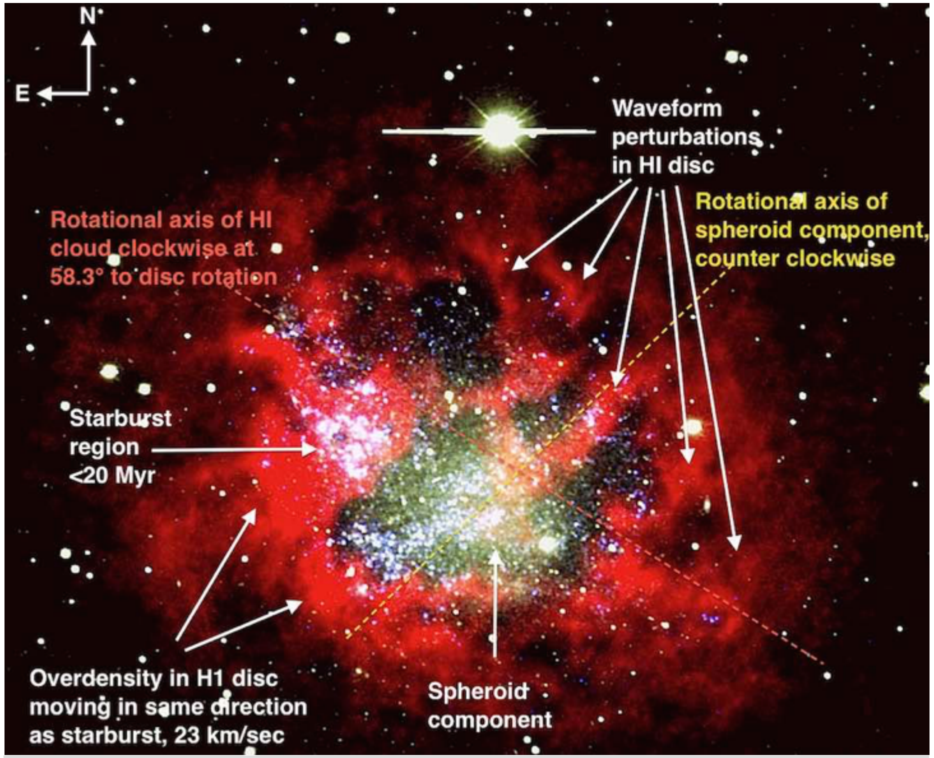
Intergalactic space, like interstellar space within a galactic halo, has significant reserves of hydrogen. Much of it clumps into the form of CHVCs or compact high-velocity clouds. These are akin to biologically dormant pathogens that float passively in the air until they come into contact with a suitable host.



UKS 2323-326 is in centre. The star on the SE edge is M_B 13.5, M_R 11.6. The bright star-like mottles across the surface are OB associations that average mag 20.4 in the visual. The circles represent the annuli of photometric studies, *r* is 0 – 44 arcsec, the annulus is 44″ to 77″, and F is the control field at r = 77″. *Source*: *Lee & Byun 1999*.

In the thin tenuities of deep space CHVCs are loosely bound atomic hydrogen clouds with little central condensation and insufficient gravitational potential to do much beyond hang together and wait for events to float by. Their internal temperatures nearly match those of their surroundings, 5 to 10 K in deep space. They are significantly affected by ambient UV radiation, which can ionise the HI atoms into free-free particle clouds. The H electrons and protons recombine again once the UV descends below 10,000 K. Hydrogen is almost entirely HI neutral hydrogen at temperatures below ~7000 K. In the region 7000 – 10,000 K the gas is a mixture of HI and HII. Above 10,000 K the hydrogen is completely ionised HII. Watch how it happens *here.*

When a dwarf galaxy approaches a CHVC at high velocity, the interaction can be nearly head-on, in which case the HI condenses toward the galaxy's core and initiates an inside-out star forming event. An off-centre slide-by interaction results in a tidally



All the elements of an off-centre starform burst exist in IC 1613 — resident HI halo of subcritical density, incoming CHVC cloud of 10^6 or more $M_\odot$ (three nearly contiguous clouds in IC 1613's case), off-centre incoming vector tangent to old spheroidal disc at XX Kpc to NNE. The three initial star formation episode ~30 – 20 Myr ago are now triggering new star formation in clusters located at the contact points of each expanding cloud surface. In time the new stars will gravitate toward the old disc and form a bimodal core.

induced star formation episode in the galaxy's halo near the point of maximum friction. In both cases the galaxy revives until the gas cloud is consumed and / or expelled. This is the main reason behind the irregular star formation epochs from galaxy to galaxy. (See chart on page 3.)

At slower encounter velocities, the CHVC is gravitationally dispersed by ram pressure stripping and merges into the galaxy's halo. Some sinks into the dwarf's mostly gasless core. If enough gas builds up there a collect-and-collapse star formation episode can occur. There are numerous instances of inside-out star formation in dwarf spheroidals: Carina, Fornax, and NGC 205.

UKS 2323-326: Untidy childhood, messy adulthood

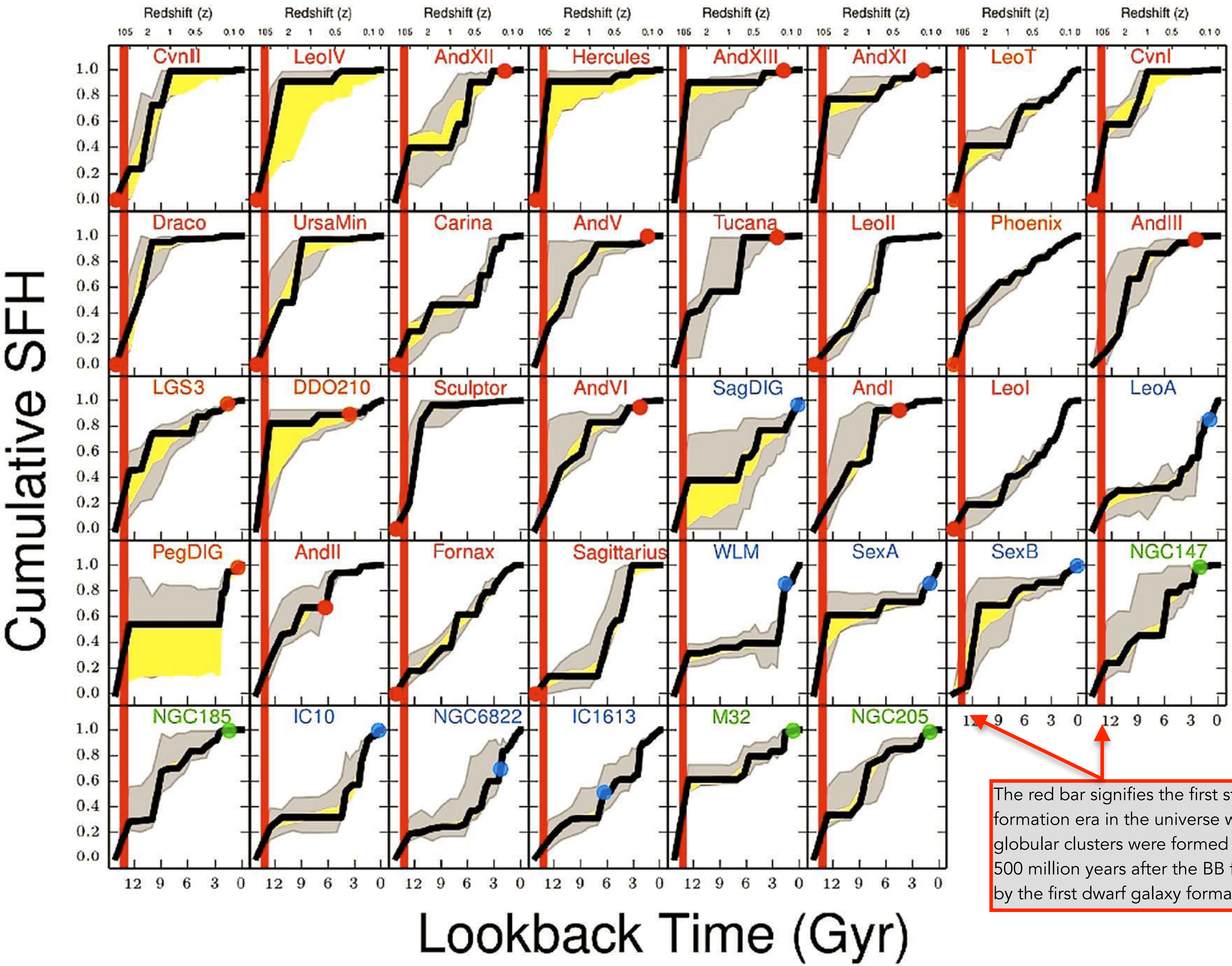
Next time you are at the eyepiece and slewing from Barnard's Galaxy to the Sculptor Dwarf, give the seldom reported UKS 2323-326 a try. If it isn't in your go-to database, key *23 26 27, –32 23 19* into the keypad.

2323 turned out to be surprisingly easy in my 7- and 8-inch Maks. For once, being tangent to a bright star is not the hindrance that such a bright star imposes in cases like the GC NGC 6380 Scorpius. For such an obscure object, 2323 certainly lacks not for identities: MCG-05-55-12, PGC 71431, UGCA 438 to name the most-used.

Surprisingly, it's an easier find than its specs would suggest. The specs say it is a 1.5 x 1.5 arcmin^2 mag 13.9 galaxy 7.27 million ly out there and somewhat beyond the Local Group's zero-velocity surface. It is more likely a outlier member of the Sculptor Galaxy group which includes NGCs 253, 247, 55, and 300. The foreground galactic extinction is only *E(B–V)* 0.014, which dims its integrated visual magnitude 13.1 to its visual surface brightness of mag 13.9 to us.

Want to know more?
The UKS 2323-326 discovery paper by *Longmore 1978* is here. *Lee & Byun 1999* identified the galaxy's stellar populations, morphology, CMDs, and surface photometry. *Mateo et al 1998* placed the galaxy in the larger context of the Local Group dwarfs and their relation to dark matter.

Star formation histories of Local Group dwarf galaxies

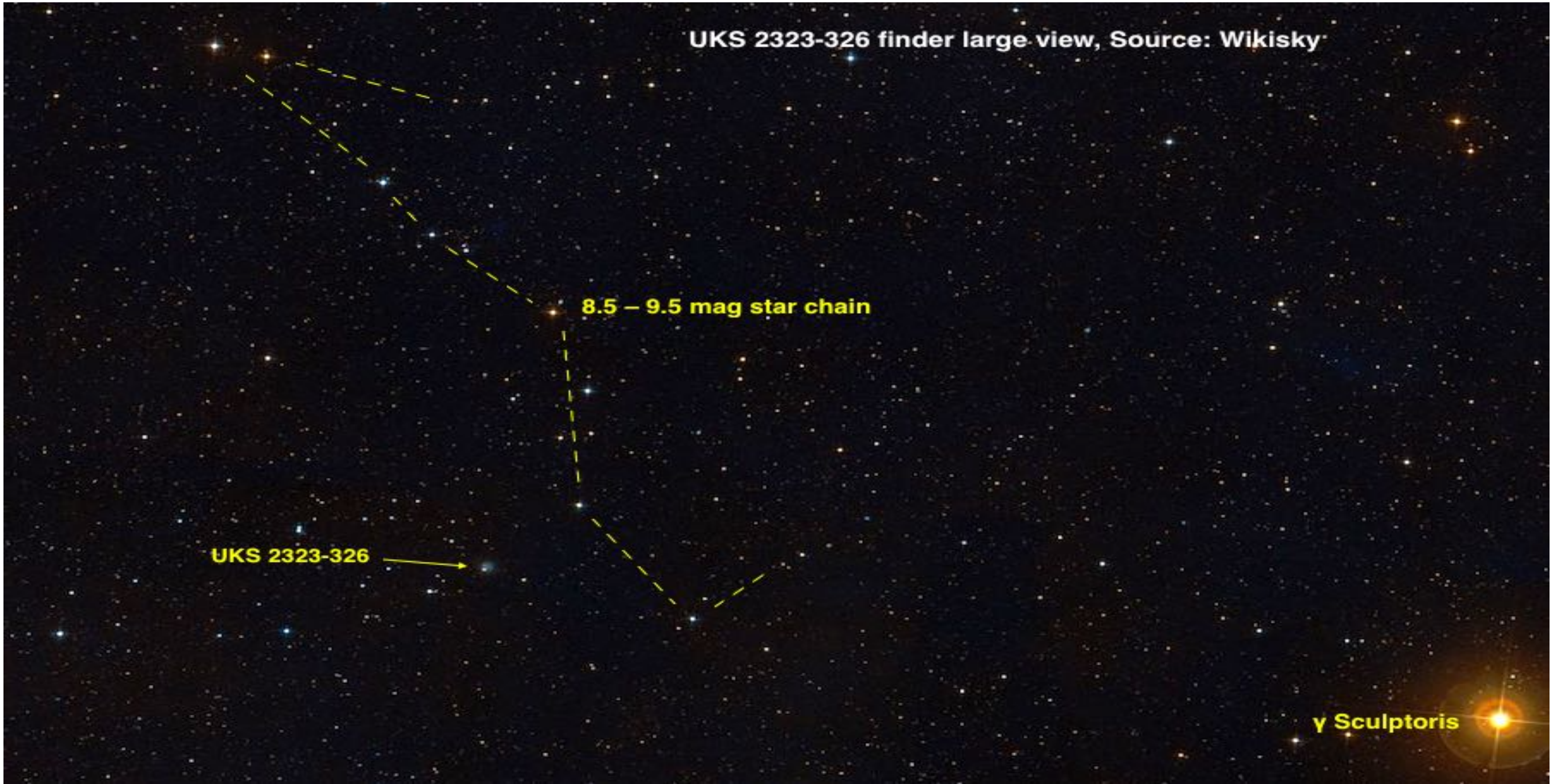


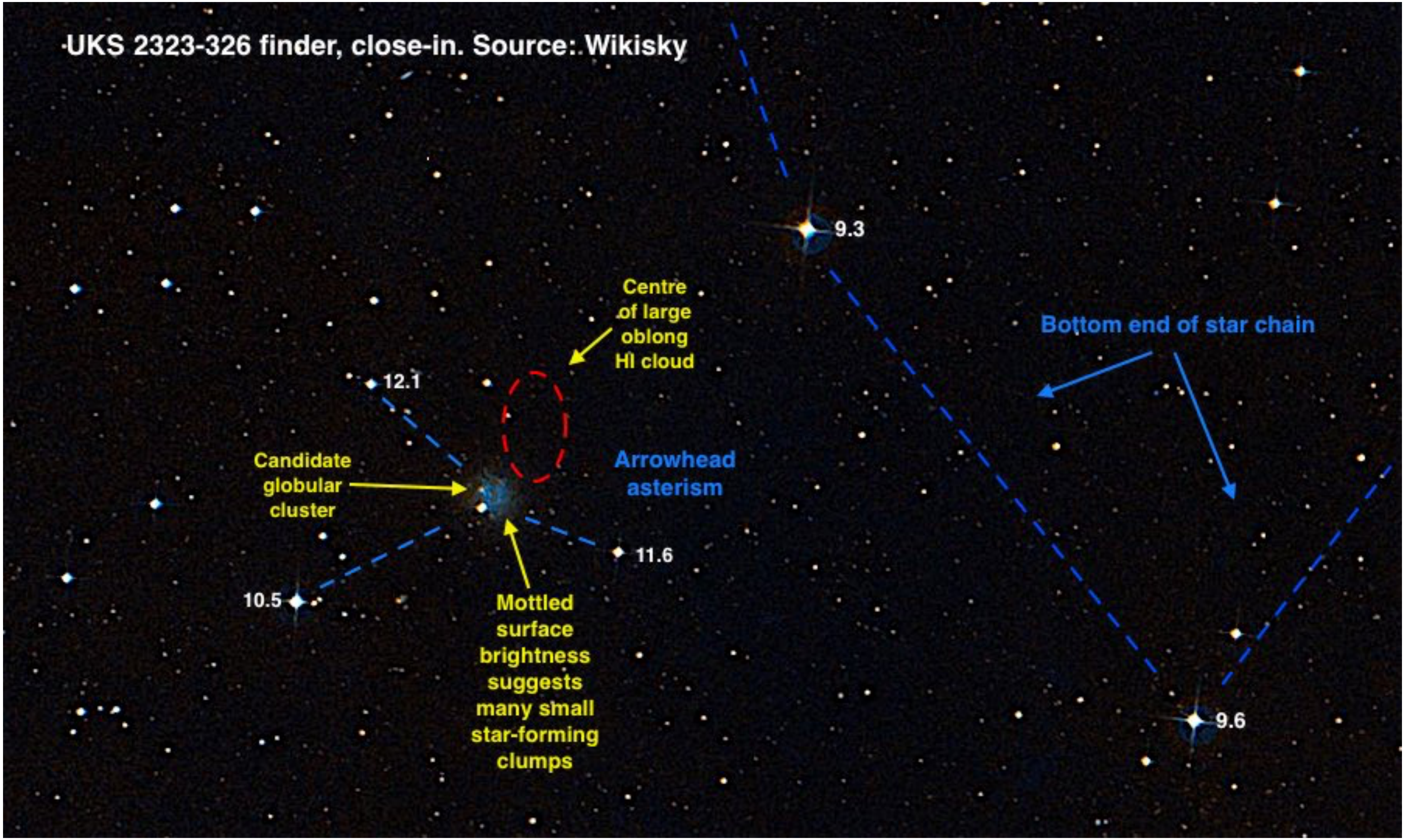
The red bar signifies the first star formation era in the universe when globular clusters were formed starting 500 million years after the BB followed by the first dwarf galaxy formation era.

In this case the distracting star turns into an asset: we look for the star with a cometary flare on one side.

Once in the eyepiece the most interesting feature on UKS 2323-326 is an active and very bright hot spot near the edge of the galaxy that's a dead ringer for a M_V 13.6 star.* Looking at the photo in Alvin Huey's *The Local Group* (thanks to which we dwarf galaxy buffs have our very own Bible) the galaxy looked so much like a very faint planetary So for the second time this cycle I applied the hoary old ruse of looking for the star with a cometary flare, *á-la* Indus IC 5152 and NGC 6380 in Scorpius, the 'second most difficult NGC globular'. Can we still call a sighting a confirm if all we see is a cometary flare? After all, it could be dust on the diagonal.

* You're in really good company when you observe this star. It was the field-calibration star during the very first shakedown run of the MAD Multiconjugate Adaptive optics Demonstrator, mounted on the 8-meter ESO Very Large Telescope on 27 Sept. 2007. Read all about it in § 2 *here*.




UKS 2323-326 finder, close-in. Source: Wikisky
9.3
Centre of large oblong HI cloud
Bottom end of star chain
12.1
Candidate globular cluster
Arrowhead asterism
11.6
10.5
Mottled surface brightness suggests many small star-forming clumps
9.6

First try at the eyepiece was a success, always a thrill with fainties. It's an easy find due to a pretty star chain above & to the left of γ Sculptoris and a Y-shaped arrow whose central star is on the galaxy's rim. I logged four or more 'definites' in averted on four different nights in the Oct 2017 dark moon cycle. The galaxy presents as a patch 1.5 arcmin in diameter so tenuous all I could see was its brightest overdensity, a non-stellar patch of ~M_V 13.5. I was impressed — this thing must be one hot galaxy to be visible to an 8-inch scope 7.27 million light years away; that's 45 times further out than the Large Magellanic Cloud. The galaxy mimics a fainter version of NGC 2438, the planetary in M46 with a bright star on the rim and three faint stellarings immersed in thin but clearly annular glow. Have a look at NGC 2438 in a 100-mm scope at about 120x and you get the idea. The delicate details of the galaxy's mottled starform surface was completely lost in the glare of the nearby tight M_V 11.5 double *ESO 23 26 27.94-32 23 31.9* which redeems itself by making it easy to find the galaxy.

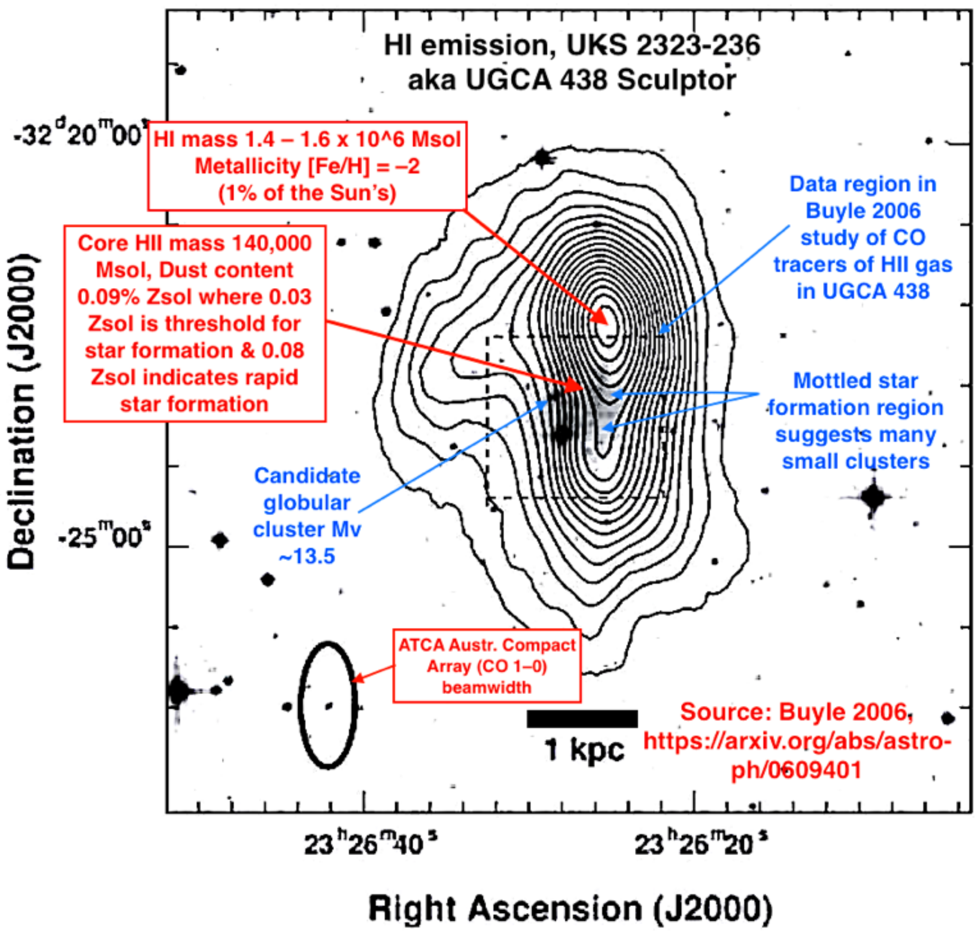
The easily visible 'spot' in the photos above is 3.5 arcsec NNW at M_V ~13.5, steady in averted, occasional in direct. It is also noticeably non-stellar even at sub arcsec diameter. If you spot the 'spot' as easily as I did in my 8-inch (and really dark skies) you are looking at 2MASX J23262847-3223040, a *suspected low-mass globular cluster*. At 7.27 Mly this would make 2323 the happy home of the most remote globular cluster most of us will ever see.*

If you are keen on tracking down globulars in distant dwarf galaxies, keep *Sharina et al 2005* ready to hand. It lists and gives positions for *182 known, probable, and suspect globulars in 57 Local Group dwarfs*. (For most of these, you will need a second mortgage on the house to buy the scope you'll need to chase them down; most are in the M81 and Cen A galaxy groups, and the Canes Venatici Cloud.) You can spare yourself a tedious slog through SIMBAD and HyperLEDA by reading Section V and downloading Table II, which lists their RA and Dec positions.

As seen through our eyepieces, 2323's flocculent central area suggests a young 4 – 5 Myr starform region ejecting its natal gas. Indeed, this remote, isolated galaxy initiated a round of cluster formation about 4 Myr ago, and has 7 red supergiants to show for it. The galaxy's Initial Mass Function (IMF) suggests that for every star of 10 $M_\odot$ there are 22,028 stars of our Sun's Mass, 1 $M_\odot$. That number of stars does not at all correlate with 2323's total current HI mass of ~1.4–1.6 million $M_\odot$, of which ±140,000 $M_\odot$ is HII. Moreover, there is a marked discontinuity between the location of 2323's central star forming region and the galaxy's HI gas. (Source: Buyle et al 2006.)

Mismatched gas densities rim 2323 with an HI halo out to 3 kpc (9780 ly) x 6 kpc (19,560 ly), and notably well-weighted toward the middle. If 2323 was plopped down between us and the centre of the MW, 2323's HI halo would occupy ¾ of the distance between us and the Bulge, stretching all the way across the Norma and Scutum-Crux arms with room to spare. Vertically the cloud would occupy a surface about the dimensions of the entire Sagg Teapot. A 1 cm^2 column from us all the way through the densest part of 2323's HI cloud would total about twice the approx. density of a 1 cm^2 column of our Earth's atmosphere from sea level to the 60 km level. The entire HI cloud would be invisible to us unless our eyes were tuned to the 60 to 100 µm bands where dust emission occurs. Even then it would be about as faint to our eyes as the Sculptor Dwarf is to us visually at about 40x in a 4-inch scope.

* *Gullieuszik 2008,* p.2 top left.



Star forming is a very inefficient process. Much of the available gas is too thin. Much is blown away by the first stars' radiation. And much is too far away to self-gravitate along with the blossoming star cluster. As a rule of thumb, in traditional galaxy spiral arm star formation, only 3% to 5% of available HII actually ends up in stars; the rest finds its way back into space. Hence, unless dwarf galaxies do things very differently, 2323's gas resources might produce seven <3 Myr old 5 – 25 $M_\odot$ O stars, but not 22,000 $M_\odot$ of smaller stars.

The O-plot thickens: 2323's CMD shows a metallicity of [Fe/H] = –1.98 but an [α/Fe] ratio of –0.9. This suggests the galaxy has a much higher proportion of iron from ancient white dwarf Type 1a supernovae than alpha elements typical of core collapse Type II supernovae and asymptotic giant branch (AGB) stars. 2323's offset HI patch is very old unprocessed gas dating back to the Reionization era, but the galaxy's central emission reveals a star-formation epoch that extends from $z = 3$ (~11.3 billion years ago) all the way to us at the eyepiece today.

2323's optical -vs- near infrared CMD reveals 7 blue supergiants <4 Myr; 38 red supergiants from >4 to <100 Myr of which a few may be AGB supergiants <6 Gyr; and 37 AGB giants ranging 500 Myr to ±6 Gyr. The plain-jane red giants on the bottom right are less useful for dating purposes because they can come from several generations of stars; instead, their real utility is establishing 2323's metals content. The red giants span M_{NIR} 20.4 to 21.7. Sparing you the tedious maths, 2323's stars born between 4 Gyr and 10 Gyr have a mixed metallicity averaging [Fe/H] = –1.7, or less than 2% of the Sun's, while the galaxy's overall metallicity is –1.98 or ~1% of the Sun's.

The verdict

1. UKS 2323-326 has been making stars for 10 billion years but we don't know exactly when or in what types of star-formation scenario.
2. There are a great many very old low-mass Solar-like and smaller stars in that galaxy which are important clues to 2323's remotest origins, but which we cannot fully know because they are too faint. UKS 2323-326's brightest blue and red stars roughly match the blue and red loops of a

Padua isochrone with an age of 30 Myr.

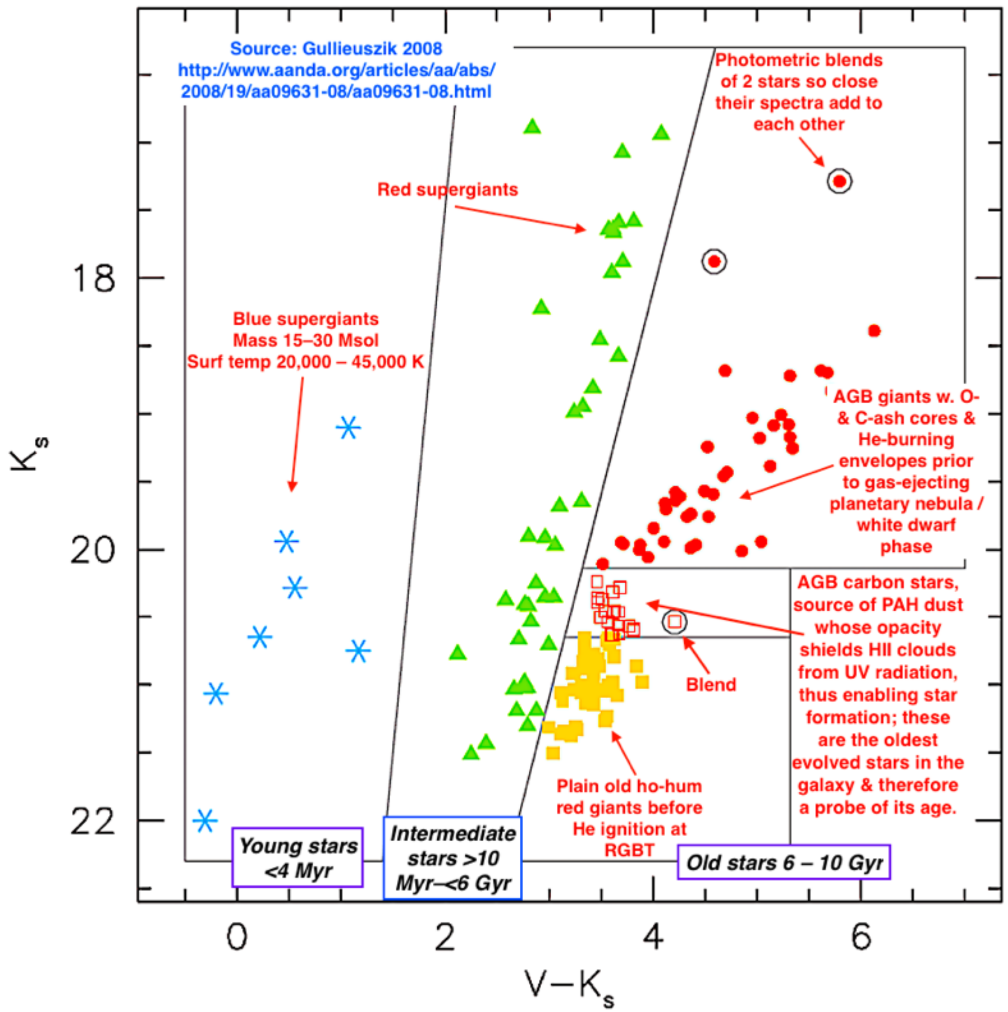
3. The brightest main sequence at $V = 21.5$ (about 1 mag below the brightest blue supergiants), which indicates an age of 10 Myr. These stars formed less than 10 Myr ago. The RGB shown in the $I(V–I)$ diagram of *Figure 3* shows that (a) the bulk of the stars in 2323 were formed before a few Gyr ago,(b) a small number of asymptotic giant-branch (AGB) stars above the TRGB were formed a few Gyr ago; and (c) the galaxy underwent a rapid star-forming event starting 10 Myr, likely in consequence of an interaction with and absorption of a CHVC of $>10^5\ M_\odot$.

In the figure to the right, what about that odd clump of open squares in 2323's CMD? These evidence the spectral energy distribution and CMD location of very late AGB carbon stars. To us, carbon stars are those wonderful rubies so roseate in an eyepiece field filled with crystalline whites and thin blues. Carbon stars remind me of that wonderful Italian Renaissance dictum that a woman is the most beauteous when she wears a splendid jewel on a plain dress. That comes to mind every time I see the lovely tiny ruby that sits alongside Mimosa in the Southern Cross.

But why should 2323 have so many of them?

Carbon stars are the life-blood of the universe. They are cinders burning down to the last ash. But without them we wouldn't be here. In their last throes of emissive life they dredge vast quantities of carbon to their surfaces, and carbon is the nucleus of galactic dust. Deep beneath an AGB's envelope carbon stars are helium shells burning around a core of inert carbon and oxygen ash. We have considerable quantities of carbon and oxygen in our atmosphere and in our bodies; some of it came from carbon stars.

The envelope of a carbon star is thin and yet cool; the helium-burning shell beneath it is >100 million K, but, figuratively speaking, it



Source: Gullieuszik 2008, Fig. 3 and all text in § 3.

is thinner than the crust on our Earth in with respect to the mantle and core beneath. Large in diameter but very thin, its heat spreads thinly in the envelope above.

Carbon is avaricious. It has four outer electrons available to bind with other elements; technically, it is a tetravalent allotrope. Most of a star's carbon is used up in making CO or carbon monoxide. Fatal to us it may be, but CO is vital to what we know about galaxies. CO is the second most abundant molecule after HII, and cohabits with it in the same clouds. While HII emits energy only in the UV, CO is visible as four very very bright, very narrow bands from the near IR to UV. It is the most accurate tracer we have of HII cloud location and composition. Almost all of it comes from carbon stars (a small proportion is from core-collapse supernovae). Carbon stars have the largest overabundance of carbon over oxygen, so there's scads of it left after CO production.

Carbon is also allotropic — it will bond to anything that will hold still long enough. Astronomers are a bit more prim when labelling the progeny: polycyclic aromatic hydrocarbons, or PAHs. There are hundreds of them in space, some with amazingly long chemical chains.

Creosote in the sky

It may seem outlandish to say that 2323 is creosote in the sky, but there's some aptness to the idea. Carbon compounds make dust in the clouds where it lives. Dark dust absorbs bright light, especially UV light. The heat carbon wrings out of photons warms the carbon compound. Which attracts hydrogen and oxygen. Which makes water ice on the surfaces of the carbon compounds. Which locks up a lot of heat energy from the surroundings into an atomic structure that doesn't much like to give up heat. That is one reason why the interiors of dusty HII clouds the coldest places in the universe (1 – 4 K). That is another way of saying that the energy density in the middle of a dark molecular cloud is so low that the surrounding gas cloud can infall from densities of a few atoms per cc to a million atoms per cc. At 10,000 atoms cm^{-3} the cloud mass is strong enough to quench turbulence. At ±100,000 atoms cm^{-3}, so many free electrons are grabbed by molecules to make bigger molecules that the cloud loses its electrical conductivity; in consequence the cloud's magnetic field loses its strength. Without the disruptive forces of turbulence and the shielding effect of magnetic fields, gravity — finally — has free reign. Star-making begins.

Galaxies mature by converting a certain proportion of their vast primordial but unreactive HI atomic hydrogen into moderately reactive HII molecular hydrogen. The sequence of events varies considerably from galaxy to galaxy. In the broadest terms, galactic growth produces internal supersonic turbulence and ambient magnetic field pressures that must dissipate to below subsonic levels while ambipolar diffusion ceases before gravity can initiate collapse into new bursts of star formation. In some cases, like IC 1613, an approaching CHVC begins to self-collapse as it enters a dwarf galaxy's halo. In IC 1613's most recent starform event, the ancient spheroid encountered three 10^6 to 10^7 $M_\odot$ clouds between 30 and 50 Myr ago; collapse and star formation occurred while the clouds were more than 6,000 light years from the old spheroid's outskirts. As can be seen in the Daniel Weisz chart above, IC 1613 has quite a history of these starburst episodes — three since $z = 1$.

Why do dwarf galaxies exhibit such unpredictable patterns of adding mass? Add to this the mystery of larger dwarfs having fewer but larger globular clusters and smaller dwarfs having many small and often young globulars. Adjust for the spices of unrelated chemical makeups and instances of barred galaxies like Barnard's Galaxy with no < 7 Gyr ($z = 1$) interaction history and yet only vestigial spiral arms. Then there's the beclotted patterns of star formation patches deep inside some dwarfs but far outside the visible rims of others. Put this recipe into the oven of 4 billion years, and out comes this group of faint glows that challenge the eye.

Dwarf galaxies may seem like small-fry to big-galaxy devotees. Look how many times NGC 253 or M83 turn up in the amateur observing websites, compared with the sparse citations of, say, IC 5152, the Pegasus Dwarf, or Sextans B. Yet these little faint peewees had an outsized role in determining the way the universe looks to us today.

The mass density in the early universe was far higher than today because the universe had expanded so little from its primordial initial state. The first dark matter haloes to achieve critical density for baryonic star formation first were the haloes with enough baryonic gas mass to form 100,000 to a 1 million solar-mass stars. At the point when the halo mass density matched the critical density for star formation, the first stellar groups that formed were the globular clusters. As we gaze at them through the eyepiece today, most globulars have far fewer stars than 100,000 stars; only a few massive globulars e.g. 47 Tucanae and NGC 2808 have as many as a million stars. (The Omega Cen cluster doesn't count because its multiple-metallicity populations mark it as a dwarf galaxy core whose halo stars have been tidally stripped by the Milky Way.

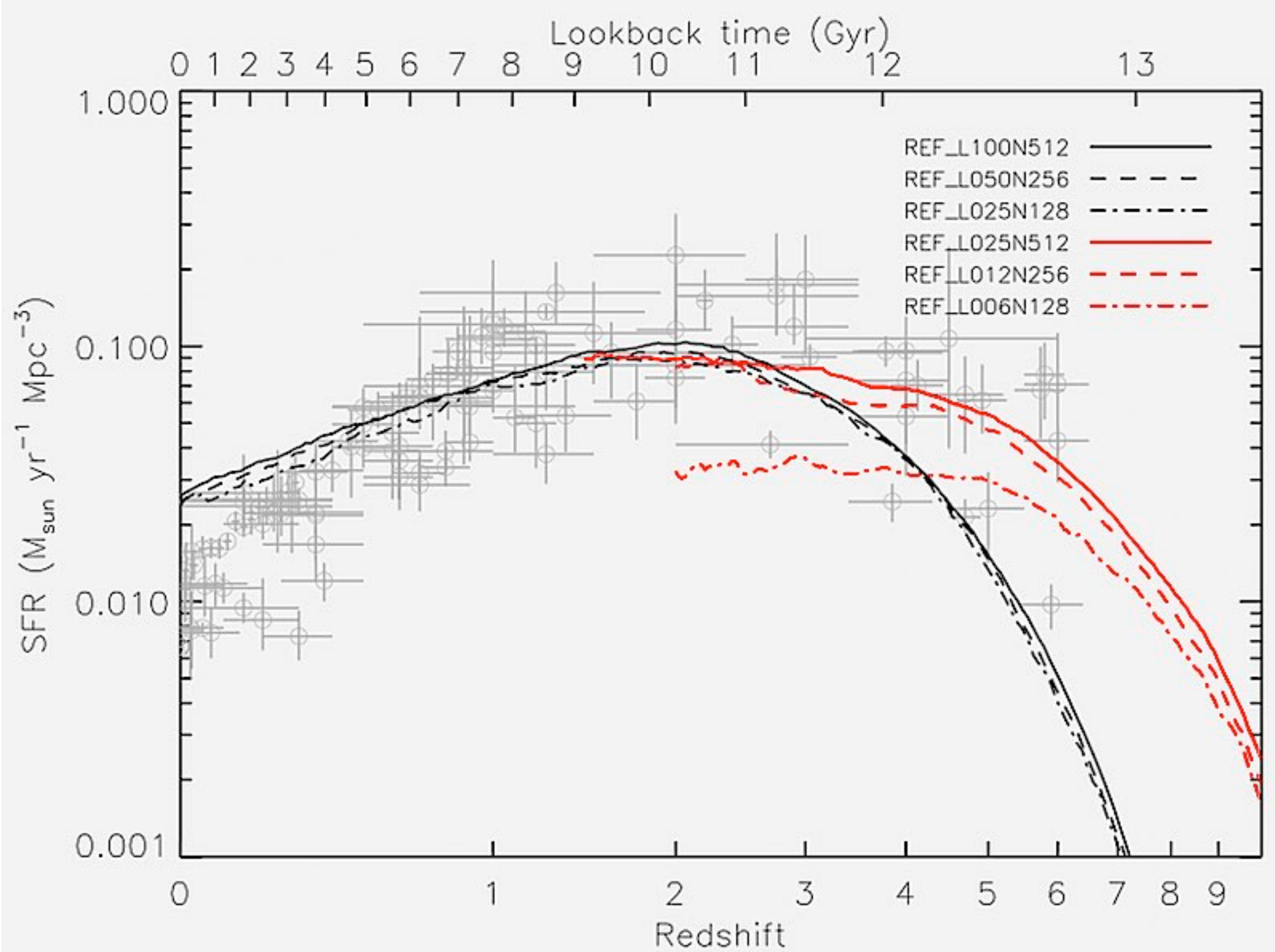
The primordial globulars' initial starburst (first generation) stars ejected most of the gas in the clusters' haloes via SN explosions and intense UV radiation. After the infant globular ended its supernovae epoch, most of the gas was lost to space. Some, however, looped high into the halo but then fell back into the cluster core, where it produced a second generation of stars. (The rule-of-thumb number of years for a complete SN-to-SN cycle in primordial globulars is 500 million years.) Globulars were already producing second-generation supernovae 12.5 to 13 billion years ago. The second supernovae round depleted the gas supply so much that most globulars today have only two generations of stars within them. The globulars later suffered the additional loss of most of their dark matter mass when galaxies formed starting half a billion years later and the galactic dark haloes absorbed the globular haloes in the course of normal orbital dynamics. Today's globulars have almost no dark matter and very little gas. They are literally running naked through the universe.

Dwarf galaxies were the next to shrink out of the expanding and therefore cooling dark matter blobs in the universe. By then the universe was nearing the 1 billion year mark in its growth. Dwarf galaxies needed a lot more time to assemble the multi-billions of solar masses of gas we find in today's larger dwarfs. Only then did they achieve critical density where rapid star formation could occur. Even at $z = 7$ we notice two effects that had a significant but contrarian effects on the evolution of the universe. One was that the ambient temperature of the intergalactic medium was cooling, making it easier to gather together larger gas masses. The second was the thinning effect that the expansion of space induced. The two effects tended to nearly balance each other. The first dwarf galaxies needed to gather 10 to 100 times as much mass together before they reached critical density for star formation, but they managed in the end to get their act together.

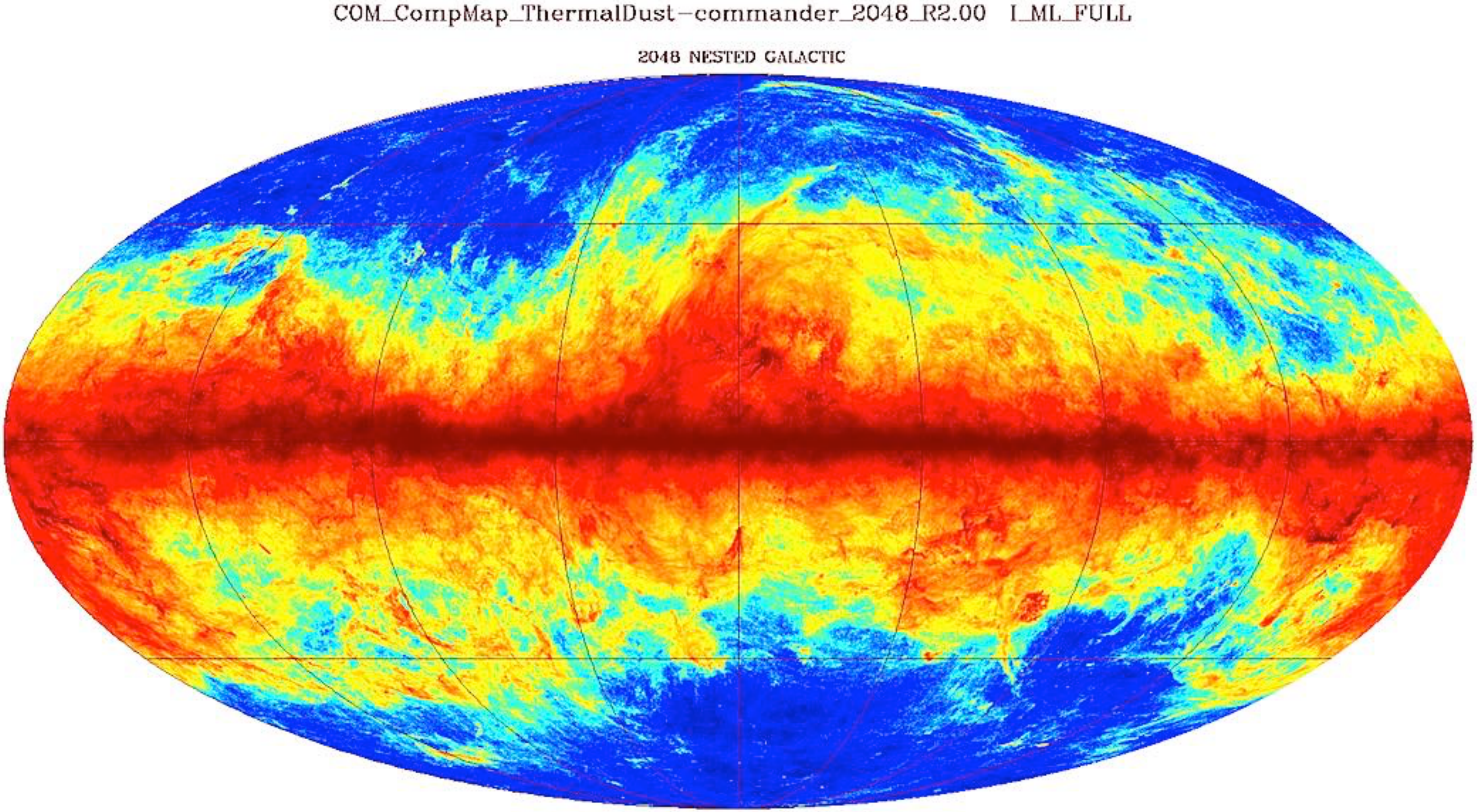
If we refer again to Daniel Weisz's star-formation chart on page 2, the red line in the far left side identifies the era when the first globular clusters began to form, when the universe was about half a billion years old. Observe that in every galaxy's evolutional history, there is a rapid rise in stellar mass in the time span surrounding that red bar.

Observe also that in almost every galaxy, star formation all but ceased for the next 1.5 to 3 billion years. This was a direct consequence of the Reionisation Era in which so much UV from early star formation flooded the universe that large gas clouds could not cool enough to condense into a star-forming core. The early dwarf galaxies and then major galaxies formed ten to a hundred times as many early O and B supergiant stars as did the globulars. When these exploded in enormous numbers starting between $z = 7$ and $z = 6$, their intense UV radiation re-ionised the gas, first in their immediate surroundings, and eventually the entire universe. The effect is called a top-heavy initial mass function, (IMF).

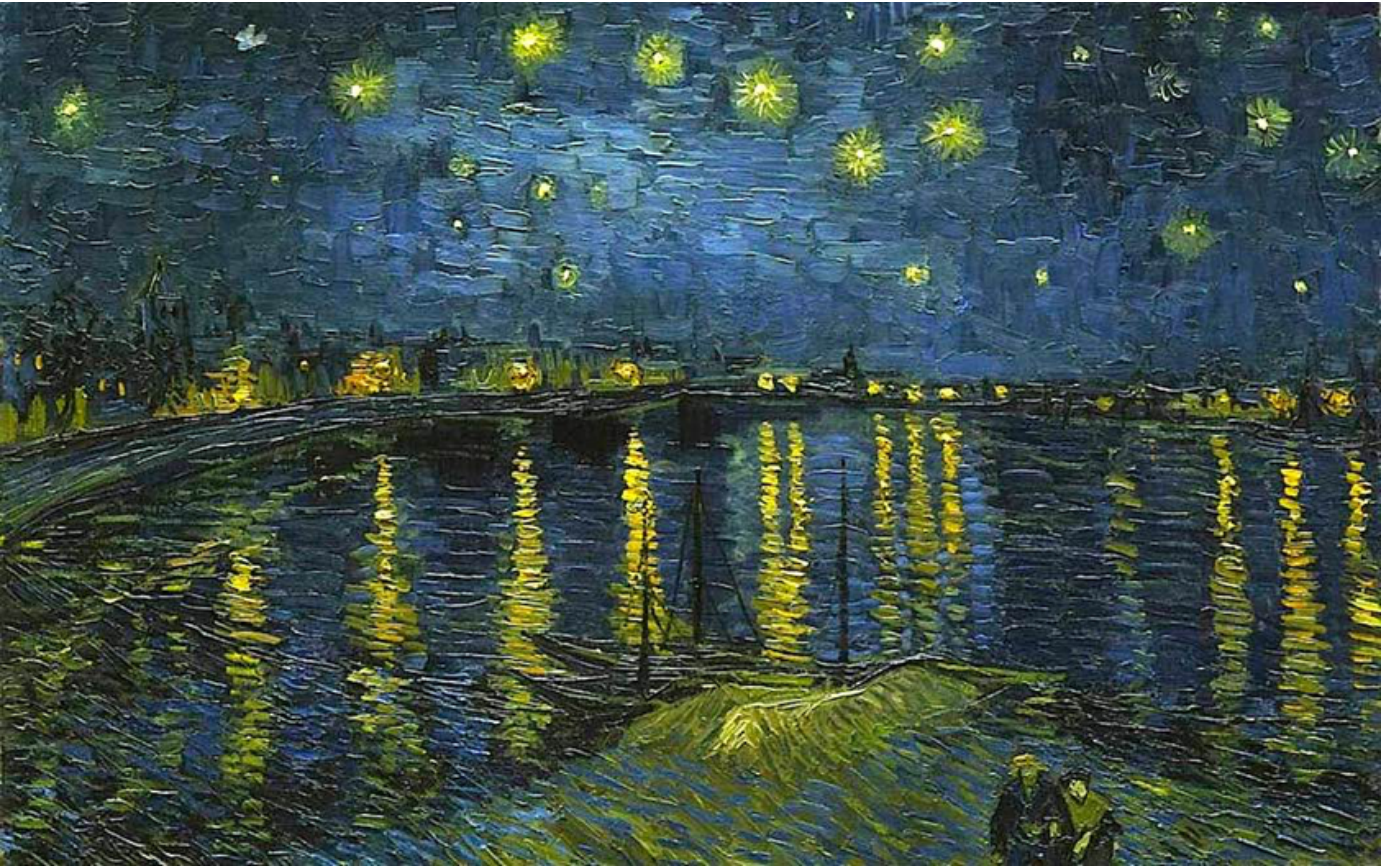
It took the universe a billion and a half years to cool to the point where its free-free electrons and protons could re-combine in numbers vast enough to feed the peak star formation era starting at $z = 3$. When the universe cooled below 10,000 K electrons could recombine with protons to form HI gas.



Star formation rates in solar masses per year per cubic megaparsec at different lookback times from z = 10 to today. The long SFR dome peaked at ~ z = 2 and has declined at about $z = 10^{-0.6}$ since then. There appears to be enough primordial HI to fuel galaxy and star formation for a considerable time yet. However, this graph does not take into account co-moving space expansion's effect on a fixed mass of gas, so the graph as a cosmic SFR forecast over the next 7 Gyr would be overoptimistic.



Milky Way thermal dust emission, Planck satellite data



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