Sky Candy

A journey through the world of astrophysics as art

Douglas Bullis

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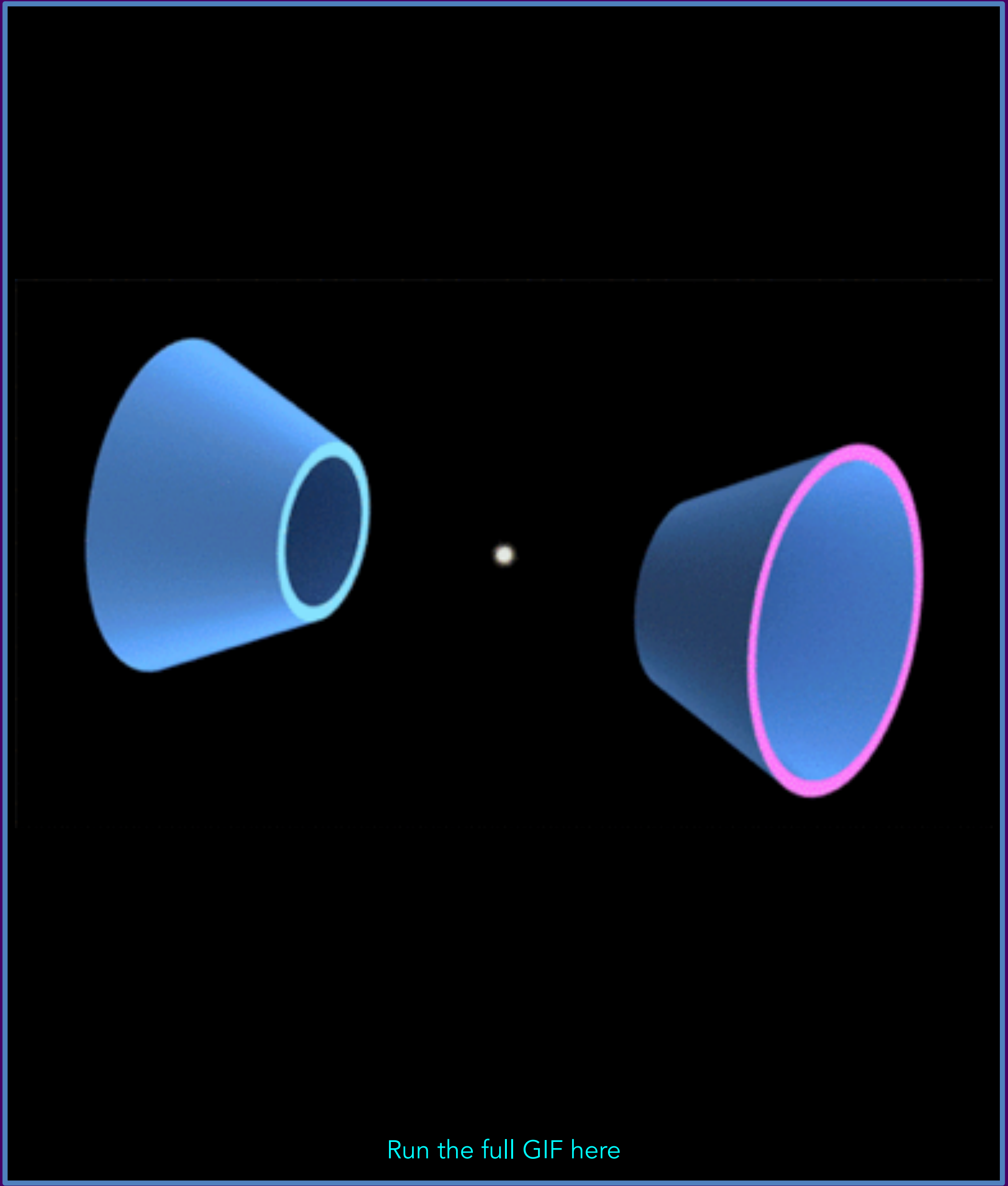
WHAT WOULD WE SEE IF WE TURNED ASTROPHYSICS INTO ART?

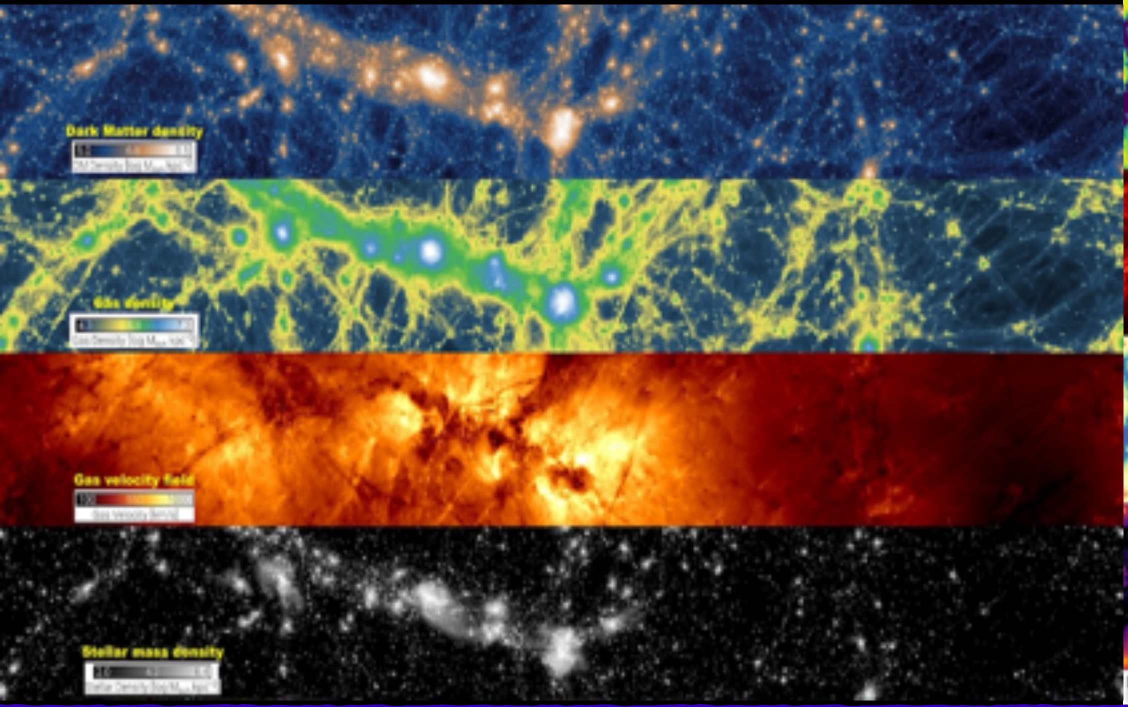


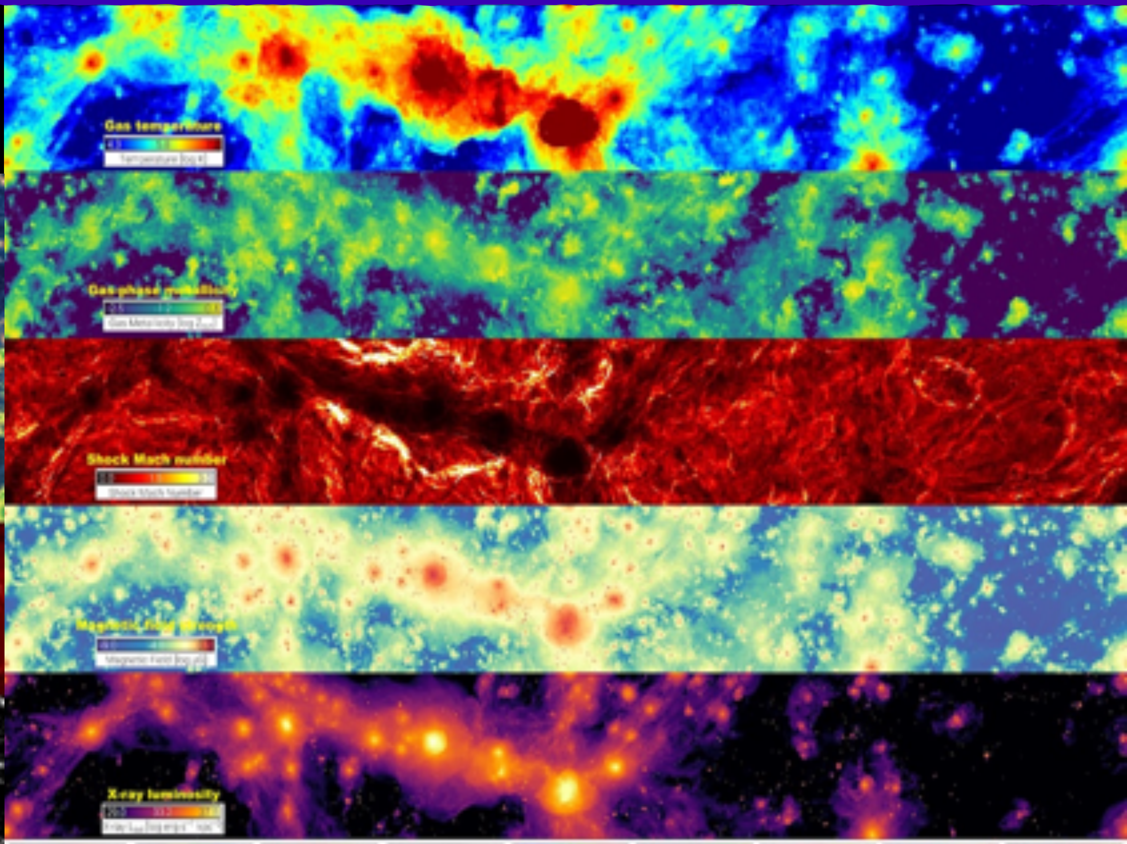
Run the full GIF here

Sky Candy

The wonderful world of astrophysics as art

Great beauty lies beyond what we can see.
Let's go there.





Douglas Bullis

Welcome to the Universe we cannot see.

We explore to discover what don't know. Then we analyze to learn what the discovery is made of and why it is there. If we can manage to avoid the next step — exploiting it for what we can extract from it — then enough of its original integrity remains for us to divine its meaning and enjoy its beauty.

In these pages we explore the beauty to be found in a very abstruse subject — astrophysics — but we intentionally avoid losing our way amid the complexity of that science so we can hold our focus on its beauty. We explore a visual terrain that until now has been known mainly to astrophysicists — the appearance of well-known objects as seen via the ninety-nine percent of the electromagnetic spectrum that our eyes cannot see. As familiar as many of us are with the astronomical images of planets, stars, nebulae, and galaxies that appear in endless variations in the popular media, those are only one percent of what is really there. Let us now go beyond these and explore what we find.

Why "*Sky Candy*"?

The title of this book might seem to trivialise two of the most compelling interests of humankind — art and astronomy. Candy, after all, provides a fleeting enjoyment which adds little net benefit to the consumer's well-being. Art and astronomy do just the opposite.

Yet why is candy consumed with such gusto and so often given as a token of friendship or love, while the same cannot be said for art or astronomy? Imagine the reaction at a wedding reception as the joyous couple unwraps a lavishly beribboned box with the words *Fabrique en Provence* imprinted in gilt with baroque flourishes, only to find inside an array of foil-wrapped photographs of galaxies, nebulae, and planets produced by the Observatoire de Haute-Provence in the French Alps.

There is a provocative inversion hiding within the silly example above. Imagine a group of children who have been allowed but a single piece of peanut brittle for their birthdays when, upon reaching their coming-of-age day, they are presented with a large box of assorted chocolates. Imagine their astonishment at such a surfeit of variety. Now go look at the night sky.

Astrophysics and art, too, might seem at opposite ends of the spectrum. Yet they share a uniting thread: art explores the inner universe; astrophysics explores the outer universe. Together they reveal to us the universe's meaning.

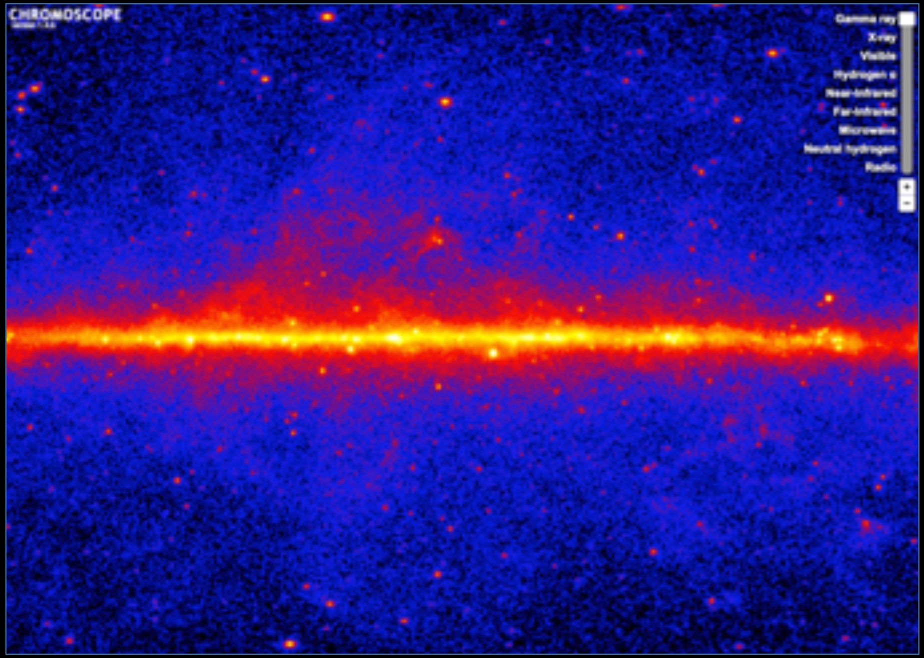
Optical astronomy, alas, has been reduced to a commodity by its commercial proponents just as art has been commodified by auctioneers and candy by marketers. It is in the bottom-line interests of commercial vendors to sell the public what they already know. For astronomy enthusiasts that means instruments that can reproduce images in an eyepiece or camera that viewers have already seen countless times in books and magazines. The amateur astronomy media are clogged with endless *Bobbsey-Twin* lookalikes of M31 the Andromeda Galaxy, M42 the Orion Nebula, the Rosette Nebula, M8 the Lagoon Nebula, the rings of Saturn's, Jupiter's Red Spot or four Galilean moons. Hundreds of different objects recur with only minor variations on well-known forms — a preoccupation with "I saw it, too" to the neglect of *why* the objects look as they do.

Optical astronomy is akin to walking out your front door and seeing a street with many houses on the other side. If you live in an apartment, substitute a row of doors across the hall and a window on either end. If you live in the country, you see the meadow and grove of trees.

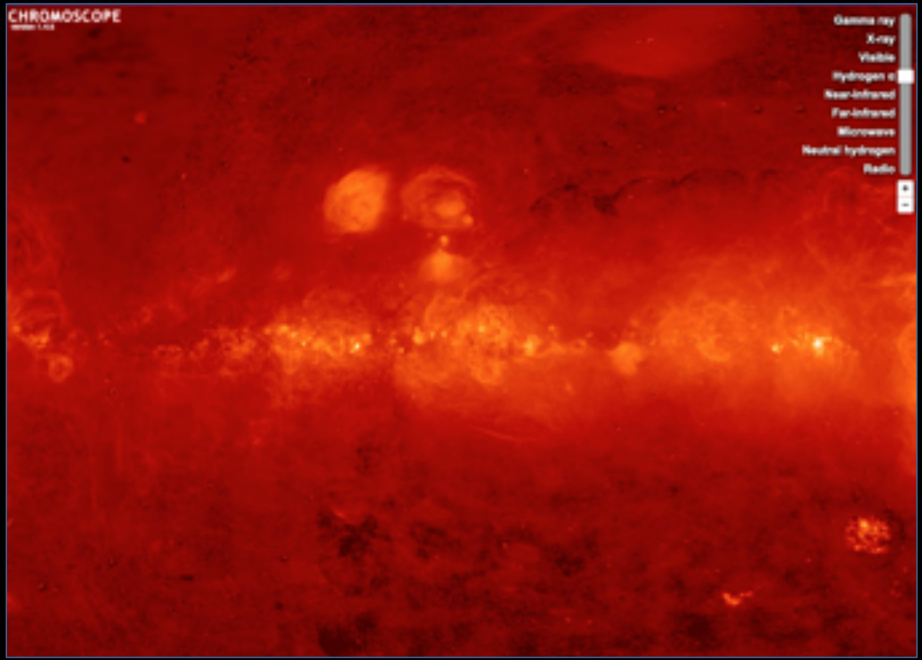
But is that really the community you live in or near? A locale with millions of people, homes, businesses, art galleries, theatres, malls, populaces endlessly on the move, moods of a myriad emotions, human wills bent on accomplishing every manner of deed that life suggests to us?

Astronomy devotes most of its attention to one percent of what really lies out there — the visual band of the spectrum, 380 to 700 nm. As recently as seventy years ago we had little idea what the other ninety-nine percent actually looked like, even though astrophysicists had discovered the mathematical laws of the electromagnetic spectrum many decades before. Now you, too, can see that wondrous other ninety-nine percent. Open a computer browser, type in *www.chromoscope.net*, and start in. Welcome to the wondrous realm of astrophysics. Now let's find its beauty.

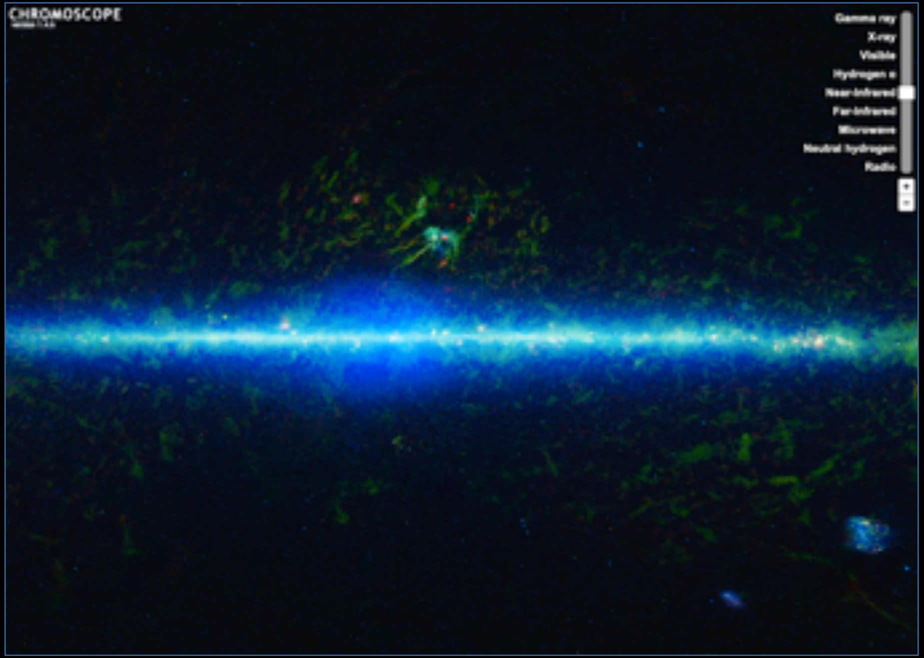
This is the central region of the Milky Way as seen in the optical band of the electromagnetic spectrum. The Galaxy's core or bulge is the bright patch in the middle, partly concealed by turbulent clouds of dust particles. The constellation Scorpius has been drawn in as a point of reference.



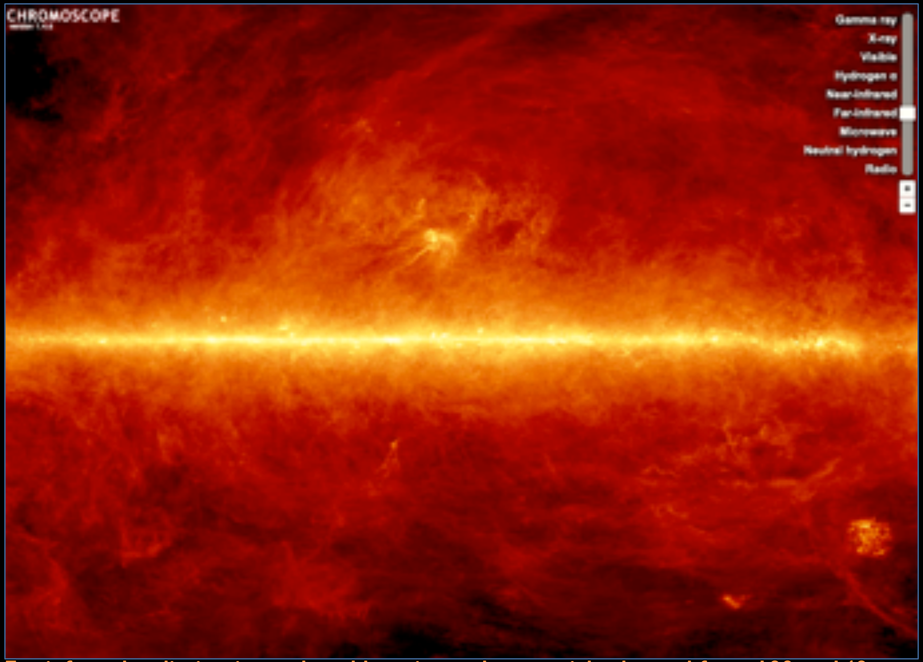
The same section of the Galaxy looks very different to telescopes that record the gamma ray band of the spectrum. Gamma rays are the most intensely energetic of all light rays. Their thermal energy measures from ten million to several hundred million degrees Kelvin. Enormous amounts of gamma radiation are forged in galaxy clusters.



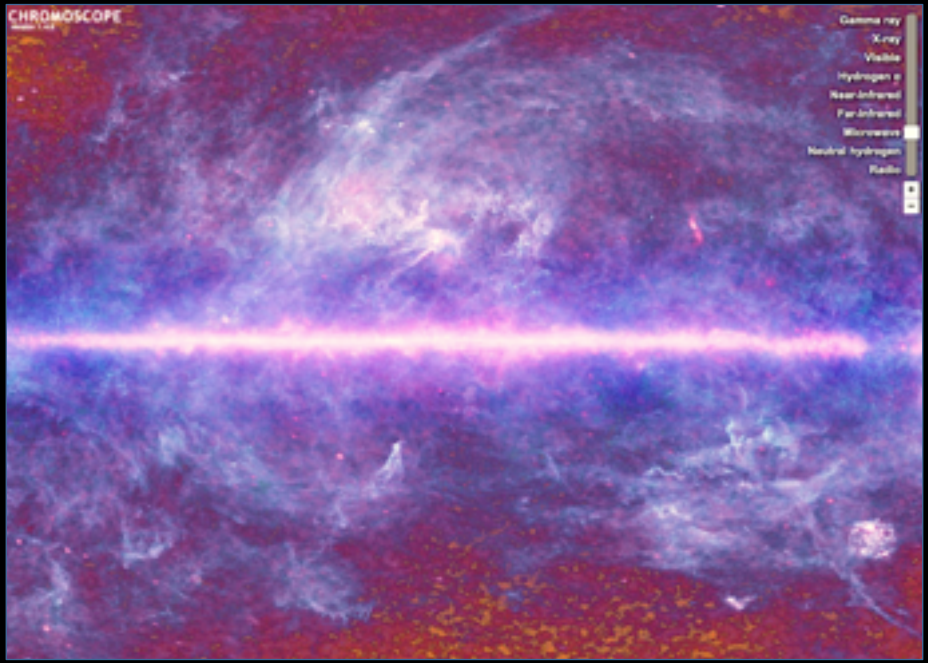
Hydrogen-alpha radiation lies just outside the visual range in the infrared band of the spectrum. It is produced as hot gas cools an loses energy. At 656 nm, Ha is the brightest hydrogen line and is produced by a great many astrophysical processes.



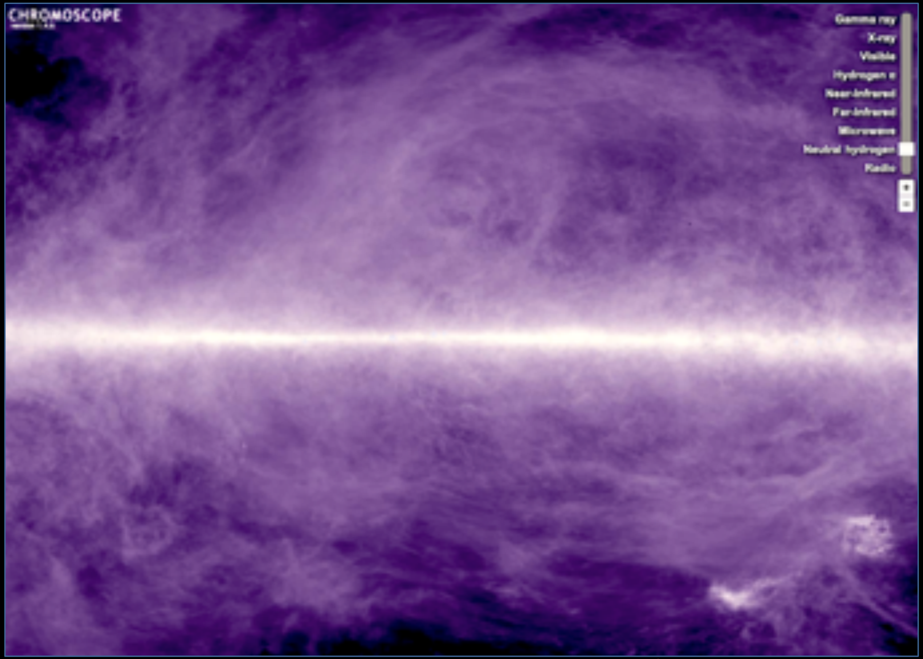
Near infrared radiation is generated by molecules such as carbon monoxide (CO) formed in cool red giant stars and ejected into space. Those same stars produce copious amounts of dust as well, so the two occur often together.



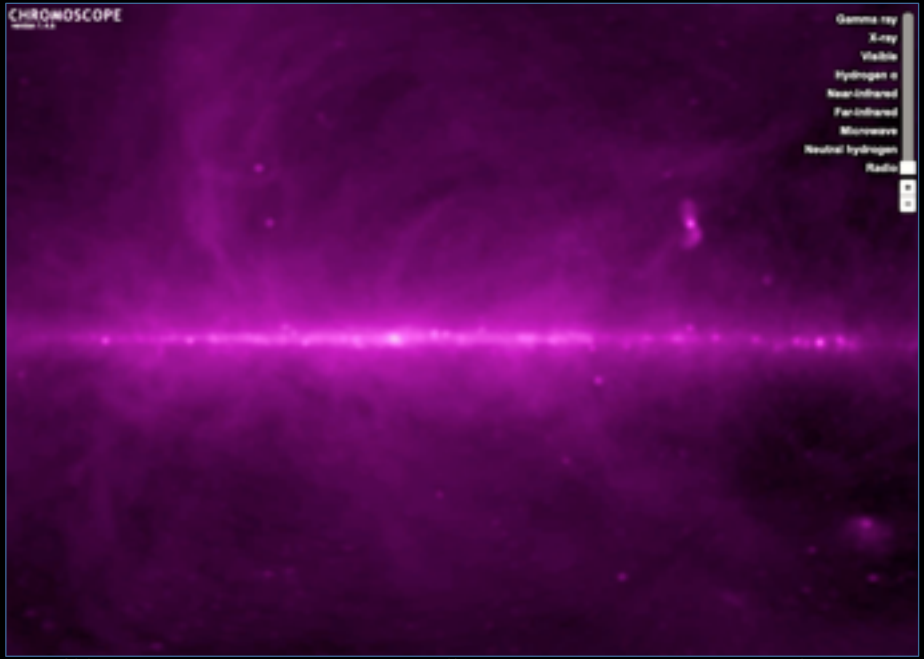
Far infrared radiation is produced by minute dust particles heated from 100 to 140 Kelvin (minus 173 to 133 Centigrade) by nearby stars. Cosmic dust is associated with molecular hydrogen clouds. Together they are the raw material that forms new stars.



The mottled patches in this image are from the Cosmic Microwave Background (CMB), the oldest light in the Universe. The CMB was originally emitted some 13.7 billion years ago. Of the 411 photons that pass through every cubic centimetre of space across the entire universe, 406 are from the CMB.

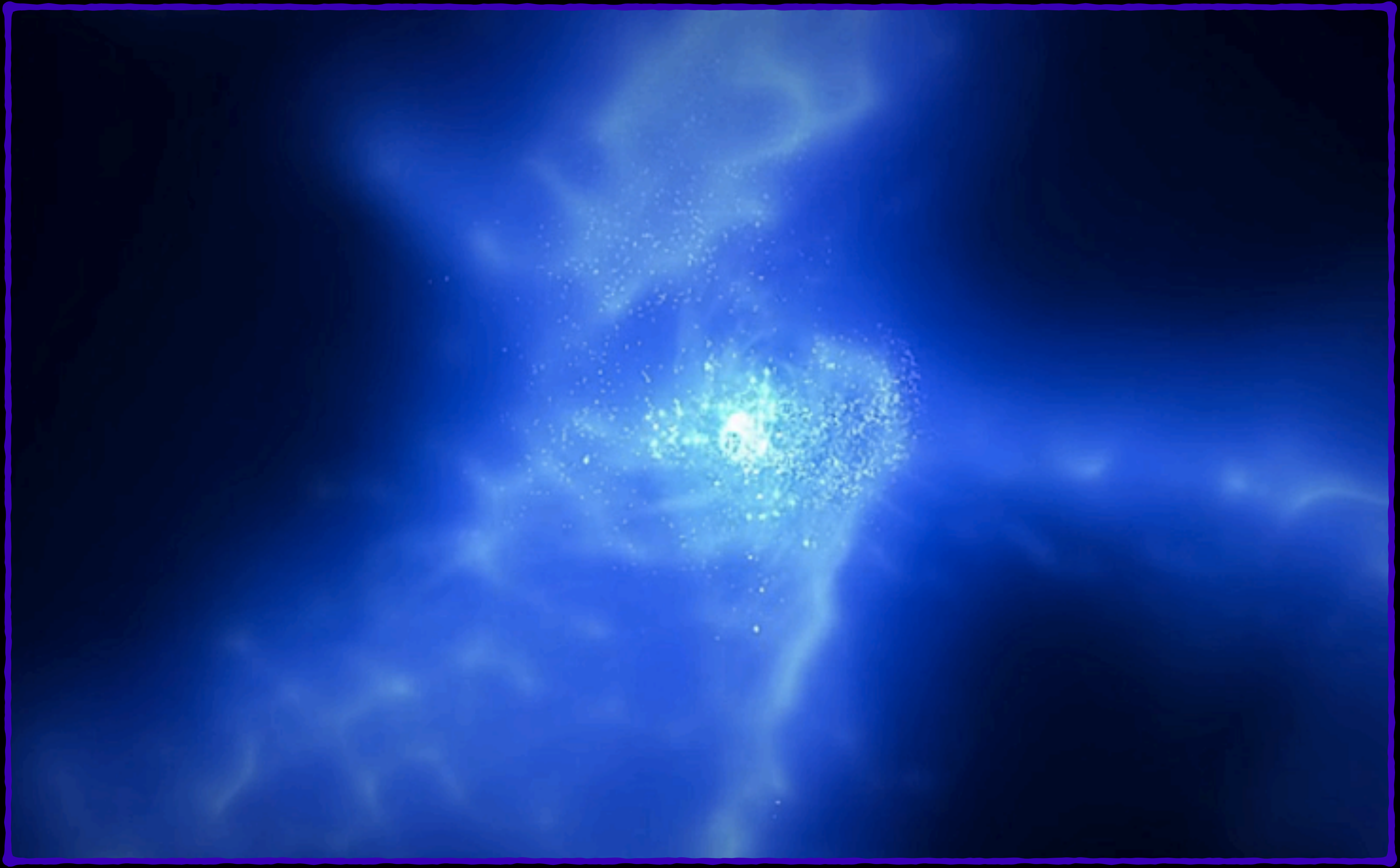


Neutral hydrogen is the most abundant gas in the universe. It falls into galaxies from deep space and collects in the discs of spiral galaxies. In 1954 observations of atomic neutral hydrogen (H i) provided the first evidence that the Milky Way is a spiral galaxy.



This 408 MHz radio continuum records diffuse light not traceable to a specific source. The map is dominated by synchrotron emission produced when electrons moving near the speed of light move in a helix-like coil as they speed along magnetic fields lines.

Long long ago and far far away, this is how we began.



while far far away and long into the future, a lad named Hubble was watching us.

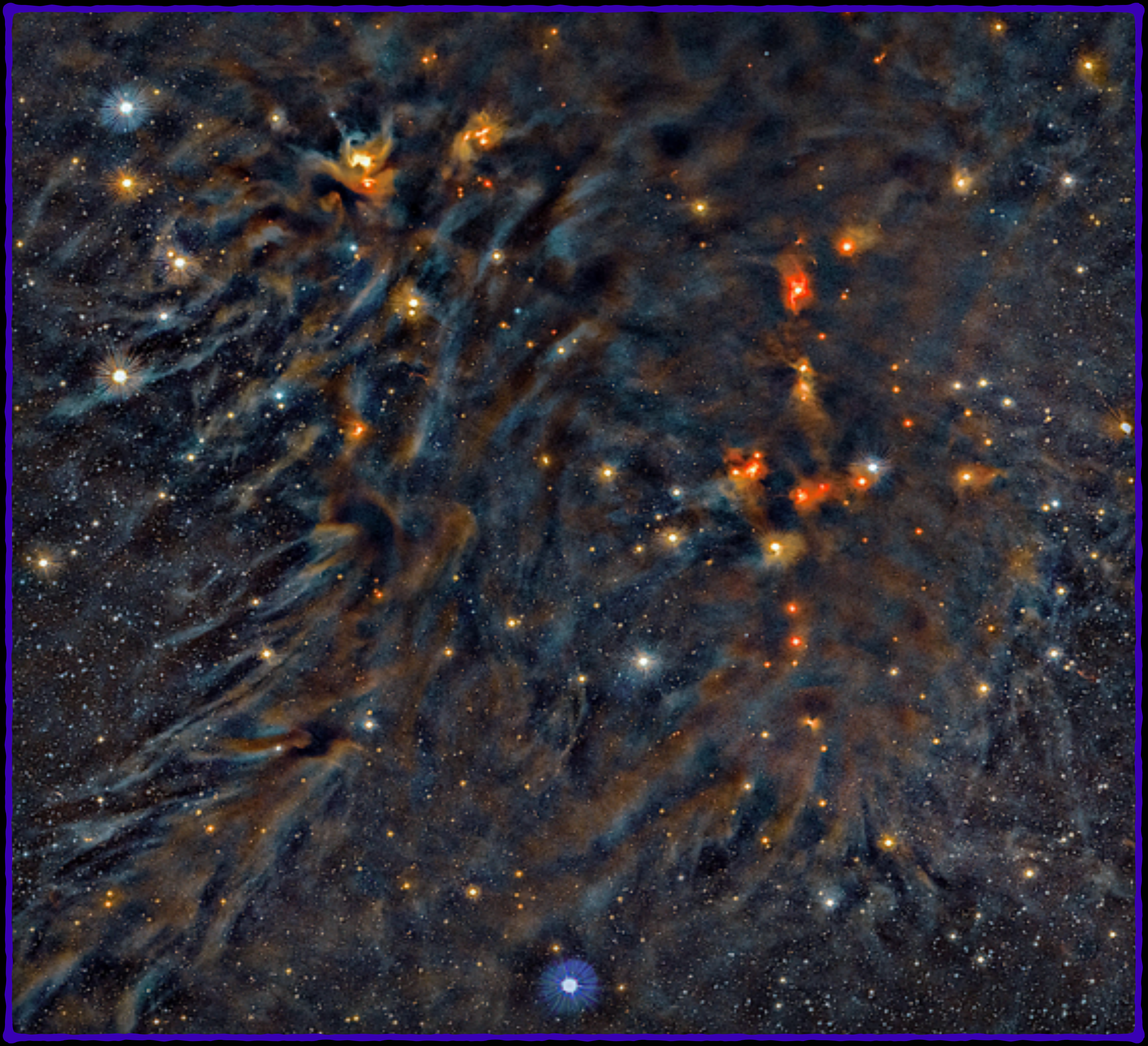
For the next few billion years we looked like this.

Click on the link in the arrow to watch a movie of the motion of cosmic gas in a small region of the universe about one billion years after the Big Bang. The colours signify velocity, from local rest (black) to 1000 km/s (bright red and white). In this early 'assembly' era of the universe's expansion, accretion and infall from the intergalactic medium of primordial hydrogen has already been pulled into the cores of invisible 'dark matter' halos. Here, stellar feedback from stellar winds and supernovae energise galactic winds that gradually erupt outwards until a number of black holes became massive enough to launch high-velocity outflows called jets—those mini-volcanos in the *TNG/ILLUSTRIS* video that enlivens this snapshot image.The video shows how stars assemble into galaxies and galaxies merge into clusters of galaxies. The structure of the universe takes shape as stars and gas produce shells, tidal tails, and galactic mergers.

When we were young we looked a fright.

Have you ever wondered what our birthplace looked like before the Sun was a star? Bewonder no longer. The complex star-forming region to the right is part of the LI688 star-forming cloud in Ophiuchus. Like most star-forming clouds, it has a dense core of molecular hydrogen (a pair of hydrogen protons but only one electron orbiting them), plus 10% and 20% of cosmic dust particles by mass, all of which are surrounded by a thick shield of atomic hydrogen. The atomic hydrogen scatters many of the incoming high-energy cosmic rays which can weaken star formation.

In this image of LI688 the core has fragmented into numerous ultra-dense clumps. While the original giant core comprised perhaps 10 to 100 atoms per cubic centimetre, the dense clumps glowing in yellow-red here have upwards of one million atoms per cc. That density is the threshold at which gravitational collapse overcomes thermal pressure and the clump collapses into star clusters containing a few hundred to a few thousand stars. It is thought that the Sun's birth cluster contained around 4000 stars ranging from tiny dwarfs barely able to glow up a steeply rising scale of masses to a top level of a few blazing hot O supergiants between 25 and 60 times the sun's mass. Almost all large young star clusters are similarly composed. Today we know only a small handful of the Sun's siblings. One of them is *90 Hercules*, a 5th magnitude star near Vega in Lyra, both named 1800 years ago by Ptolemy.



IN THE LI688 IMAGE to the left the bright white objects with halo-like rays are field stars that are not part of the Ophiuchus molecular cloud complex. Disregard them as you consider what is going on in the dusky, messy—and important—parts of the image.

Molecular clouds range greatly in size and density, from small clouds less than a light-year in diameter up to giant molecular clouds (GMCs), which are over 100 light-years in diameter and contain enough material to make many thousands of stars. LI688 is a mid-mass cloud with enough gas to make several hundred to two thousand stars of many different mass sizes from tykes to titans.

The most common component of these clouds is molecular hydrogen (H_2). Other molecules include carbon monoxide (CO), which astronomers use to trace H_2 since H_2 has a negligible electronic signature of its own), as well as organic compounds such as methanol. While dust is present throughout a galaxy's interstellar medium (the stuff in between the stars), the dust density in molecular clouds can become opaque enough to make the clouds appear like black splotches that we see in the image. Molecular hydrogen forms only on the surfaces of cosmic dust particles, so dust is a vital ingredient in star formation. The densest dark clouds in the image also contain bright red-yellow patches. These are very young star-forming regions which in time will produce bright stars like our Sun.

Until the year 2005 there were two basic models of how stars form in molecular clouds. In the *gravitational collapse model*, molecular clumps hundreds to thousands of solar masses in size fragmented into dense cores denser than 2 grams per cc that then collapsed down to the extreme densities seen in the cores of stars. When the temperature of the core gas reaches about 7 million degrees Kelvin, hydrogen fuses with deuterium (a hydrogen atom with an additional neutron in the nucleus) and releases energy. That is enough energy to support a considerable amount of outward pressure. If the cloud's gas and dust continue to fall into the young star, outward nuclear fusion pressure rises to match the gravitational pressure of the cloud and the star stops growing. The dark blobs with red-yellow patches in LI688 are what that model looks like in the real world of a galaxy.

The other model was called the competitive accretion theory. That view proposed that all stars were born smaller than about half the mass of the Sun, and that the vast range of stellar masses actually observed grew by the accretion of unbound gas from the original molecular and atomic clouds. The LI688 image gives some credence to that idea, too. The entire star-forming region—particularly on the left side—is marked by filaments of gas and dust streaming directly into the dark clumps where it looks like no stars are being born.

If a single image like the one opposite can give visual credence to two contradictory theories of star cluster formation, how do we decide which theory is right?

One clue was the detection of X-rays in young star clusters. When X-ray astronomy began in the late 1960s, the only way to get above the Earth's X-ray blotting atmosphere was by sending detectors high above the stratosphere in helium balloons. The first satellites dedicated to X-ray astronomy were Uhuru, Ariel 5, SAS-3, OSO-8, and HEAO-1. Their resolution was good enough to detect individual stars, but not to map the delicate nuances of complex star-forming regions with legions of X-ray protostars like we see in LI688. By the early 2000s sophisticated satellites like RXTE, ROSAT, ASCA, as well as BeppoSAX were good enough to suggest, but not prove, that competitive accretion could not attract enough gas onto a star to make stars more massive than about 10 solar masses (rather incongruously called mid-mass stars by astronomers). Anything heavier had to be explained by adding on another theory, that mid-mass stars collided often enough to make the required number of 40 to 60 solar-mass stars actually observed.

Adding a new theory on top of another to explain something that has never been observed was, frankly, a bit of a stretch even in the theory-thick world of star formation. Then the first millimeter-band observations of star dust in accretion discs around stars arrived in a series of images and astrophysics papers (*1*,*2*,*3*) that confirmed through real-sky observations that dust—and therefore its ever-present companion gas—could fall into stars even when the stars were rotating at such high speeds that they were close to the limit where they would start throwing off large chunks via centrifugal force like ice skaters spinning so fast they lose their balance and fall over). That's science for you: new observations throw old theories out the window. All the elegant equations in the world are not going to help you if you don't observe what they predict.

The LI688 image also suggests something we do not see in the image, mainly because it hasn't happened yet: conveyor-belt star cluster formation.

The LI688 image readily shows that stars in a cluster form nearly all at the same time. By 'same time' we mean 'within a million years'. At the achingly slow pace at which events in galaxies tend to occur, some astronomers define 'a million years' as 'instantaneous'.

Now take note of how many tendril-like filamentary structures appear in the image. Those structures look—and indeed behave—like braided rivulets in an earthly river delta. Gas flows along them until it reaches a star or star cluster, at which point it falls into the accretion discs around young stars. If a molecular cloud is massive and elongated enough, star clusters will form along its length more or less in sequence as fresh gas pours in after existing gas is turned into stars. The conveyor belt will keep on forming new stars and clusters until the cloud is exhausted. To see what it looks like in simulations, see *1*,*2*,*3*,*4*.

SQUINT A BIT and LI688 is a work of abstract art you might enjoy if it was a painting on the wall across from your desk.

A bit of cosmic grooming improved that.

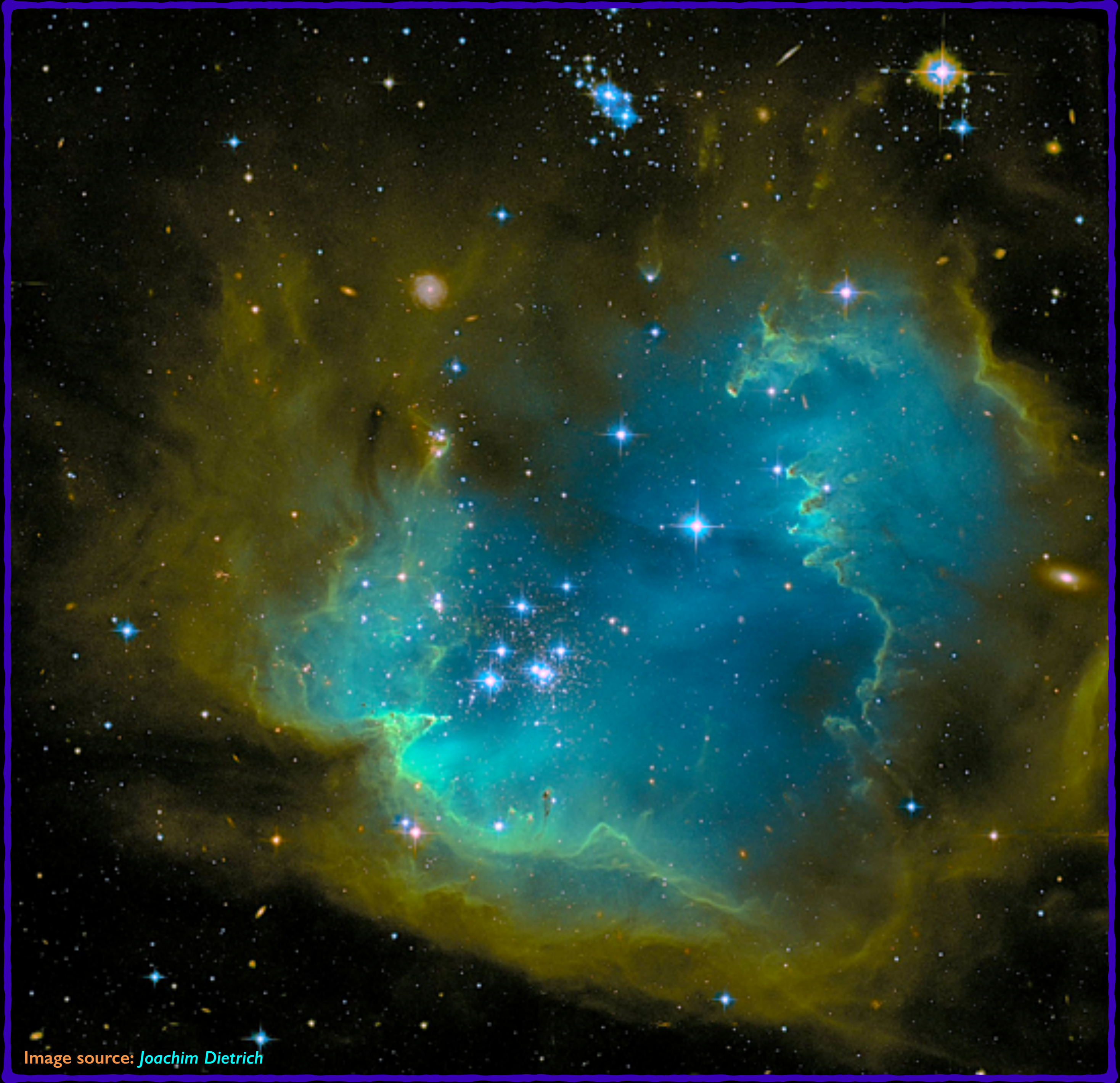


Image source: *Joachim Dietrich*

NGC 602 in the Small Magellanic Cloud is a young star cluster only a few million years old clearing out the cluster's unused natal gas via UV radiation pressure and turbulent shock fronts. As the radiation pressure accelerates gas and dust particles away from the cluster, the shock fronts force the cluster gas into the surrounding gas that was in the area long before the cluster collapsed into stars. Now the cluster is forcing its excess gas into the local medium, creating broad, long supersonic shock waves. Since the pre-existing gas and dust was clumpy, the radiation pressure wraps itself around denser pockets of gas, creating turbulent shock surfaces. Pressure in shock fronts can become so high that secondary star formation occurs.

So-called 'pillars of creation' reveal very dense local pockets that look like mountain peaks in space. The combination of supersonic shock waves and a sudden rise in temperature induces secondary star formation that we see as brightly illuminated tips pushed into comet-like compression surfaces, at the tip of which infant stars are being born. The resemblance to the Hubble Space Telescope's famous 2012 'Pillars of Creation' photograph is not accidental—nearly all star clusters that formed out of a molecular cloud that collapsed into stars endure the gas clearance phase that we see here approx. mid-way through the cycle of expelling unused gas back into space.

The non-uniformity of gas/dust clouds which quietly reside in galaxies is clearly evident not just in the rugged shock fronts and pillar-like structure we see here, but also in the markedly non-uniform density of the cluster stars themselves. Few open clusters have the ball-of-stars look of ancient globular cluster. Instead they have the inchoate look of NGC 602.

Soon enough it was time to find a home of our own.

In their heyday eons as glitter-box gems, star clusters shine for multi-millions of years. But what do they look like in their infancy?

The debris of multiple generations of star clusters that have come and gone across billions of years leave an astonishing—and beautiful—haze of dusty debris. Technically called 'galactic cirrus' these clouds are fiendishly difficult to photograph. Their only light comes by reflection from the cumulative light radiated by the entire Milky Way disc.

The dust grains are astonishingly minute given the seeming murky densities in images like this. Most are smaller than the particles in braai (barbecue) or cigarette smoke. The reason the clouds look dense is that they are much larger than we imagine. The three blobby pockets here are about the size of a ball stretching from Earth to the nearest visible star, Alpha Centauri, 4.367 light years away.

Only a few percent of a cold molecular cloud of dust as dense as these clumps collapses into stars. The rest is eroded by intense starlight, shredded by magnetic fields, and dissipated by stellar winds back into a warm (5000 to 10,000 K) galactic soup to try again another day.

In Beverly Lynds' dark cloud #122 here we see the ferocious ultraviolet sear of nearby hot stars blowing dust back into the galaxy. A hundred million or more years from now, the gas and dust seen here just might possibly return to much this same state, only to be blown away again. Again and again, till one day they might finally ignite. Patience is the #1 job skill in a dust particle's resumé.

Image: **Martin Heigan**.

At first glance this clean, well-lighted place looked pretty good.

THE GIANT M16 EAGLE NEBULA is a massive evaporating bubble of gas and dust. Inside it these glowing 'Pillar of Creation' clouds are remnants of a spectacular star burst that made a young open star cluster (out of view above this image). The inky sculptures seen here are evaporating as UV ultraviolet starlight from the star cluster abrades away their woolly cumulus shapes.

But there are illusions hidden in these. The bright tips are very young stars made by the compressive power of the larger cluster's massive blue giant stars; these baby stars may be young and bright, but they are about the same size as our Sun (which in star mass terms is a dwarf star).

This Hubble Telescope infrared (IR) image reveals that the murky dust columns in the famous 'Pillars of Creation' image might be better described as a mammoth icebergs of gas and dust. They are actually brutally cold inside—5 to 50 Kelvin. Their bluish surface gas is much hotter, 10,000 K and above, hence their glow. The pillars will evaporate completely in about 100,000 years, leaving only a sprinkle of tiny stars as evidence of their former grandeur..

We had been warned to check out the neighbourhood first,

Even after many years of gazing through our telescopes, looking at the starry sky still thrills us with the mystery of so much complexity. Why is it all there? We wouldn't see the stars and planets deep within these gravid clouds of dust and gas, but we would certainly feel their heat. So we make infrared telescopes to see the heat.

See what we lived in before we were born.

Infrared light travels little hindered by dense dust. Above is the left-side region seen in IR . Incandescent glowing dust now becomes veils of silk and gauze thinned by stellar winds. By observing worlds very different from our own, we grasp the sheer good luck of living within a cool, comfy, windless region called the Local Bubble.

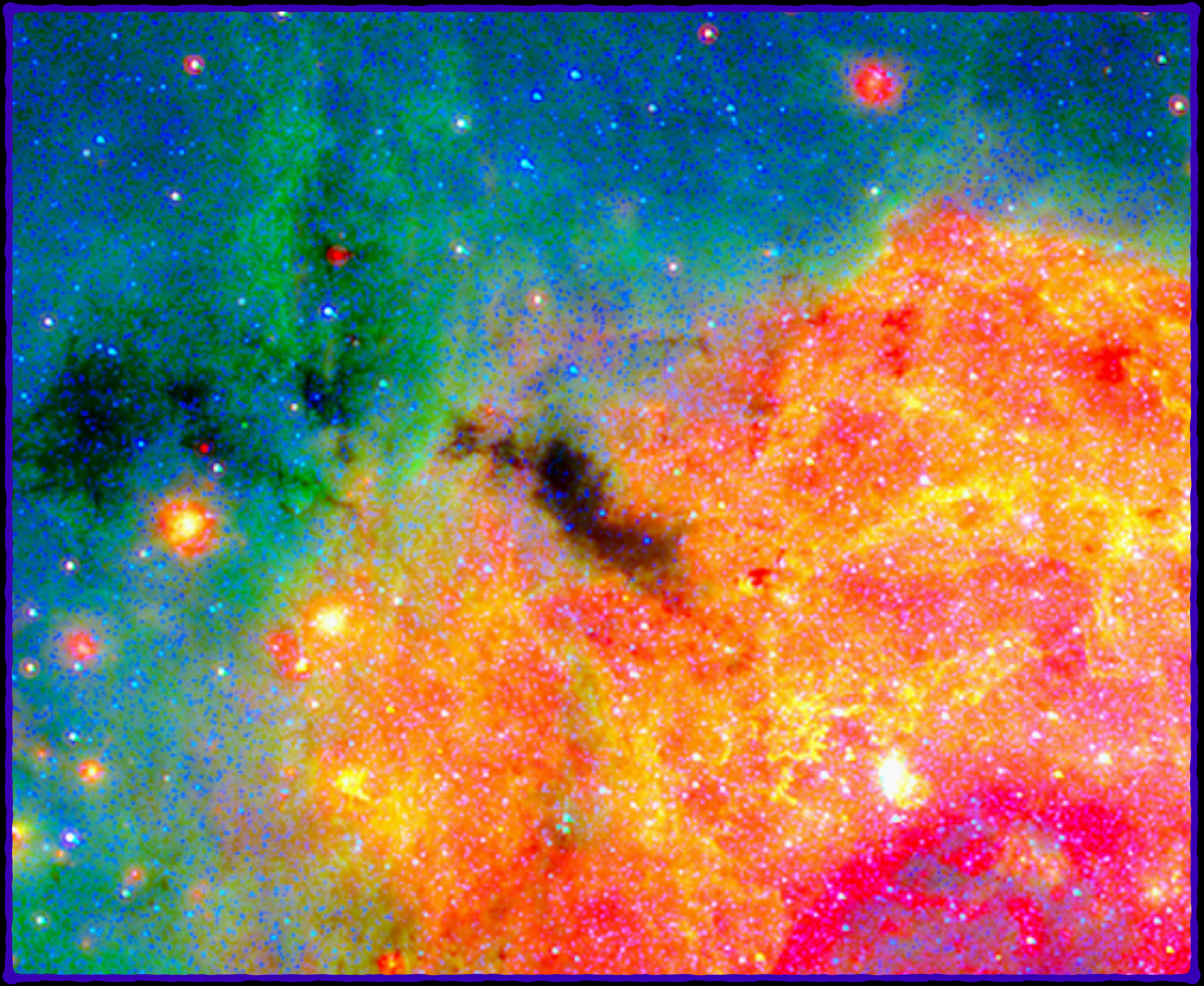
so we dipped a toe in the local water to see if we should jump in.

GALACTIC BUILDING BLOCKS don't come in compact, tidy, frogpond bundles. But put them all together and the end result is much the same—a messy, eye-pleasing limn that illumines as it beautifies.

High-mass stars might die as dazzling supernovae, but their births are mysteries garbed in murk. They form in very dense, cold clouds of gas and dust that can have up to 100,000 times the mass of the Sun. Regions like this one–called The Brick because it is a building block made out of gas and dust—are so dense that they might better be called mud puddles in the sky. Initially devoid of stars, this molecular cloud blotters the light from a flamboyant background nebula.

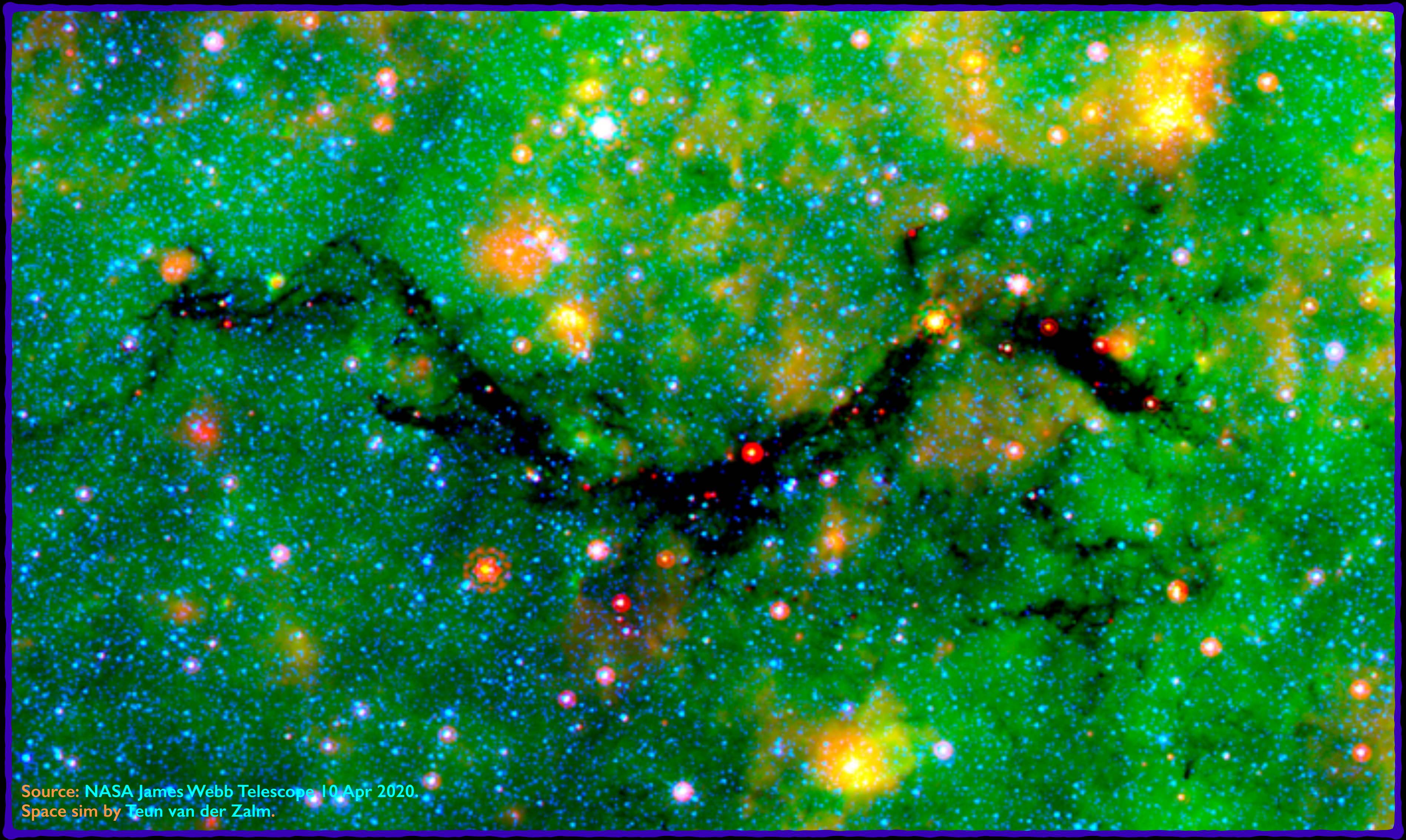
Made of gas with a dash of dust, molecular clouds are the baptismal fonts of baby stars. When their densities reach 1 million atoms per cubic centimetre, they can even block out the infrared light which usually propagates through dusty environments—hence their name: IRDCs or infrared-dark clouds.

Given the moniker 'The Brick', the IRDC centred here weighs in at over 100,000 times the mass of the Sun. It isn't forming any stars yet, but based on its density and volume, when it does form stars it will explode into a YMC – Young Massive Cluster literally ablaze with the youth of muscle and energy that on Earth wins Olympic Gold Medals.



Source: NASA James Webb Telescope website image 10 Apr 2020.

There we learned that if you think small, smaller is what you become.



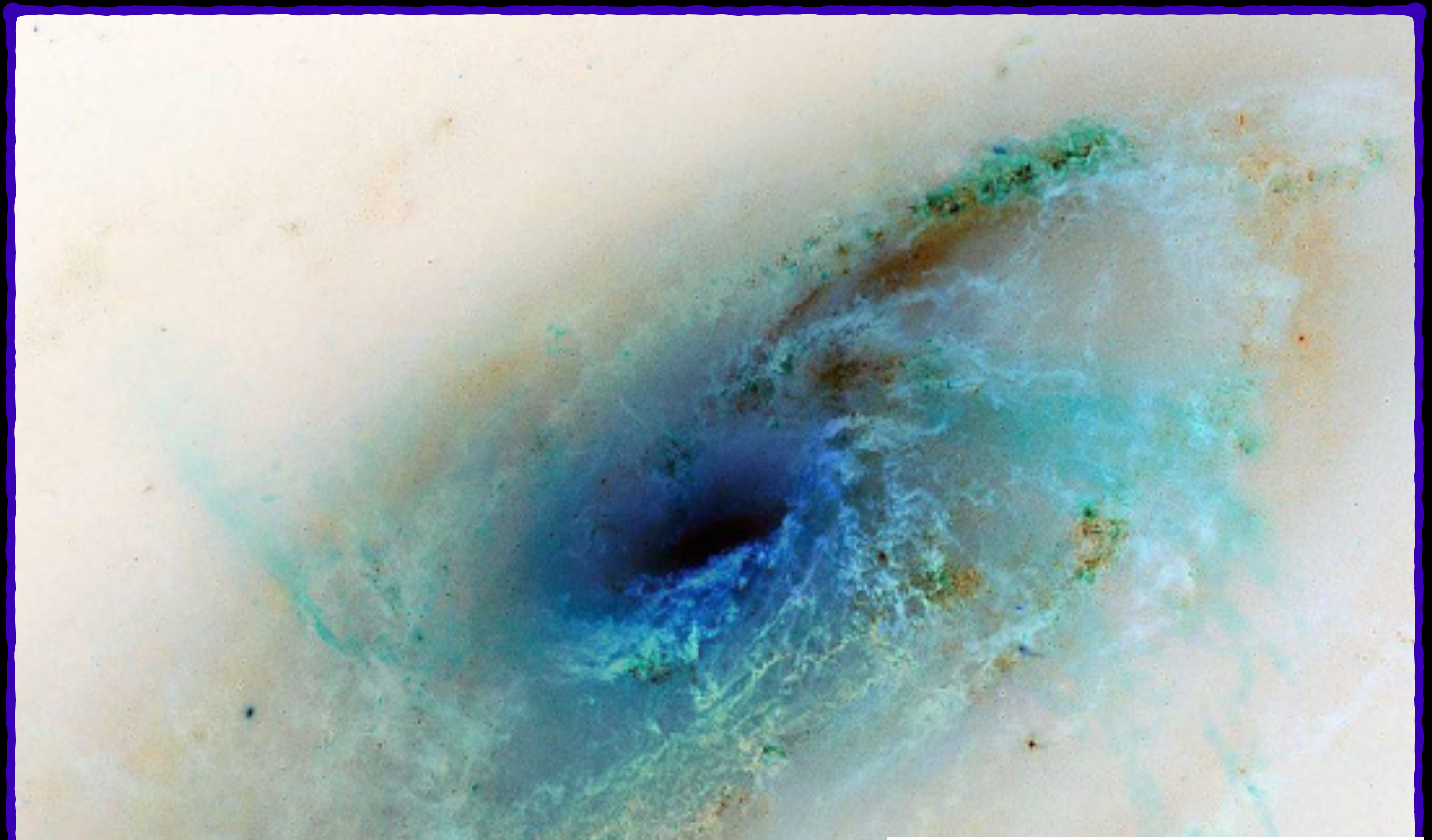
Source: NASA James Webb Telescope 10 Apr 2020.
Space sim by Teun van der Zalm.

THE SEAHORSE IS A FILAMENTARY CLOUD being squeezed from both sides by dense, turbulent gas clouds busily forming stars. Only the filament's solenoidal magnetic field is holding the pressures at bay. But this slowly dissipating flux tube is being crumpled into disconnected lumps. When magnetic support is lost, stellar turbulence quickly shreds dust filaments to bits. If the gas masses were above a certain threshold, stars could form. But here, they just didn't have the mass. In this infrared image from the Spitzer Space Telescope, the blue dots are nearby stars undimmed by dust, while the red dots are distant stars shrouded in dust. Dust clumps that don't make it into stars slowly erode into ions, atoms, and tiny particles of ink.

There seemed to be no end of ponds we could swim in,

NGC 1512 in Horologium ('The Clock') is a graceful study in the dynamics of galactic bars. Several hundred million years ago this galaxy was a modest-sized cumulus-like flocculent spiral, with many short armlets and rotationally stretched star-forming clumps. The bulge was not very massive. At some point a tiny perturbation or bump occurred at the bulge's Inner Lindblad Resonance (ILR), a ring-like region where the gravitational pull between the bulge mass and the mass of the arms balanced each other. In a young galaxy a few closely timed supernovae could provide such a perturbation. The bump stretched and thickened over time into the giant, diffuse bar we see here. The pattern speed of a galaxy bar rotates faster than the pattern speed of the spiral arms, so N1512's bar has raced through the arms it connects to several times, attaching and detaching like a tough bridge player trying to find an equally tough bridge player to partner with. During any given pile-up, a large portion of a spiral arm's gas, dust, and stars are diverted in a giant swerve to orbit in long ellipses around the bulge. They completely lose their former gravitational identity, which is why bars are so filmy and smooth. Only dust manages to hold on to its gravitational integrity, hence the dark streams curling into the Inner Lindblad ring. When the infalling matter reaches the bulge it bursts into hot, blue stars. This blue ring is the same ILR that started the process so very long ago.

although one of them had a bit of a problem with the drain.



THIS IMAGE OF THE WELL-STUDIED GALAXY M106 has been artificially colour inverted to illustrate the hazards of applying a useful technique under one set of conditions to a different set of conditions. Early astronomers preferred to inspect the original glass-plate negatives produced by their telescopes rather than the typical dark-field prints we see in magazines and books. Astronomers could more easily detect very faint stars and subtleties of contrast in nebulae by examining the original negatives. They just got used to dark points instead of bright ones. Moreover, they could write notes and circle notable object on the non-emulsion side, then wipe it away when their research was finished.

But it doesn't work that way if the image is in colour. Chromatic inversion also inverts our sense of shape. The dense, dark pool in this image that looks like the proverbial Descent into the Maelstrom, is actually a brightly glowing dome-like bulge in the real galaxy. Colour inversion is a fantasy-inspiring illusion, but astronomers prefer objects to look like what they really are.

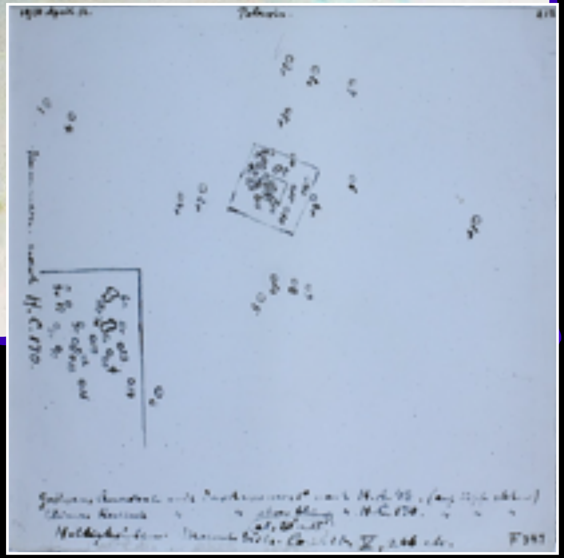
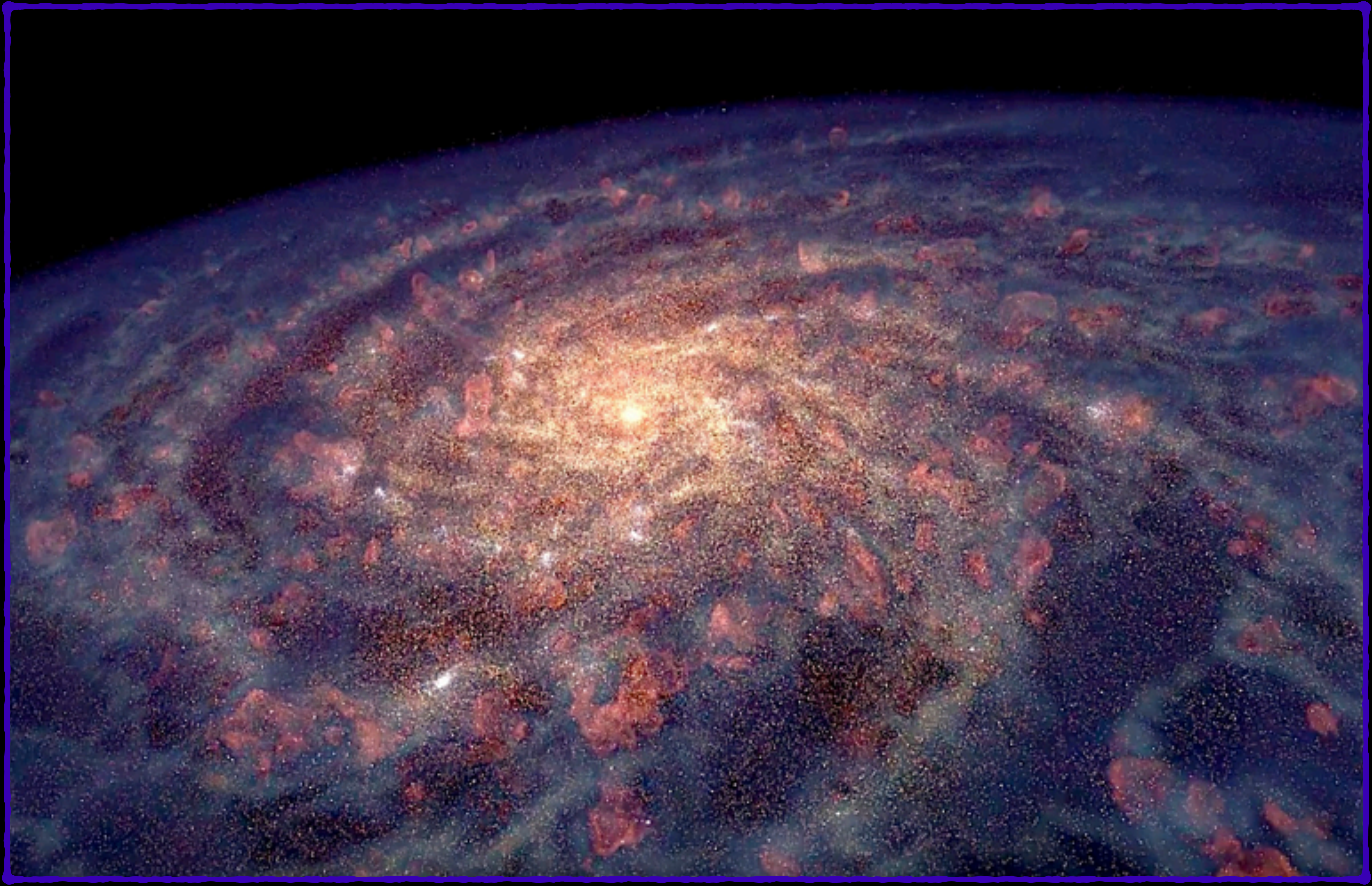
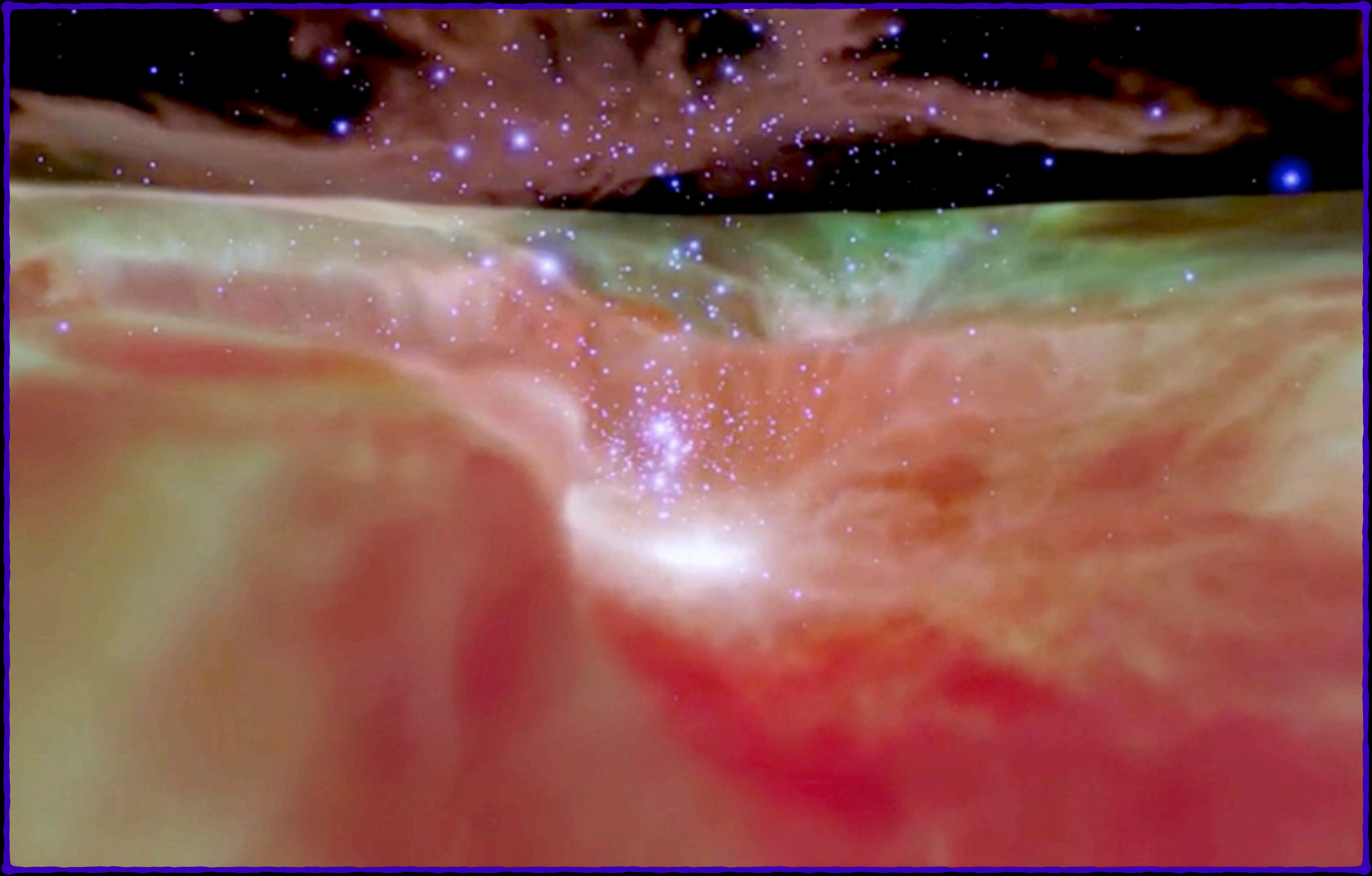


Image sources: Right: *APPLAUSE (Archives of Photographic PLates for Astronomical USE*. Far right: ESO/NASA Hubble Legacy.

Finally we found a place that had the look of a proper home



and a neighbourhood with familiar amenities.



It was so friendly we were welcomed by a comet.

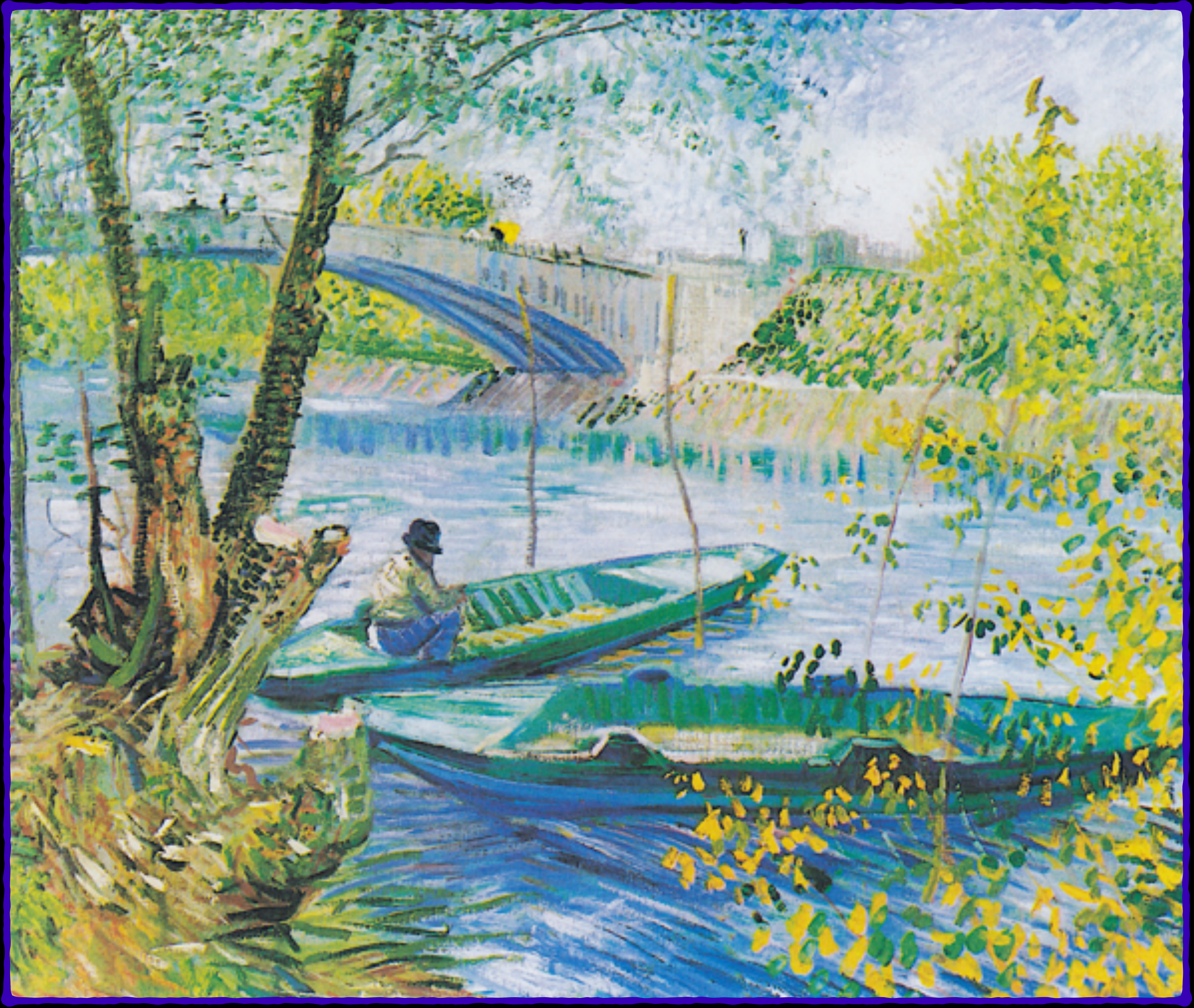
So we decided to call it home.

This painting depicts the Earth as a sphere, populated by all manner of living forms, surrounded by the ocean of the sky, all of which were threatened from beyond the sky by allegorical symbols of humankind's perennial evils. Beyond all of these was the fiery radiance of a supernal being whose energy is at once infinitesimal, infinite, and unknowable—a description which also approximates the physics of the metaphysical Is creating Will-Be which astronomers call the Big Bang.

The artist who conceived this vision is shown in the lower left corner inscribing notes on wax tablets with a stylus. Those notes and drawings on wax were rendered into the image shown here by a scribe named Volmer and artists of the Monastery of Rupertsberg in what is now Germany. The image was painted onto vellum for a book titled *Liber Divinorum Operum* (Book of Divine Works). It was the last book to be written by its author, who considered it the pinnacle of her life's work. She was Hildegard of Bingen, born 1098 as the 10th child of a modest aristocratic family. She died 1179 the most famed and influential woman in Roman Catholic medieval history.

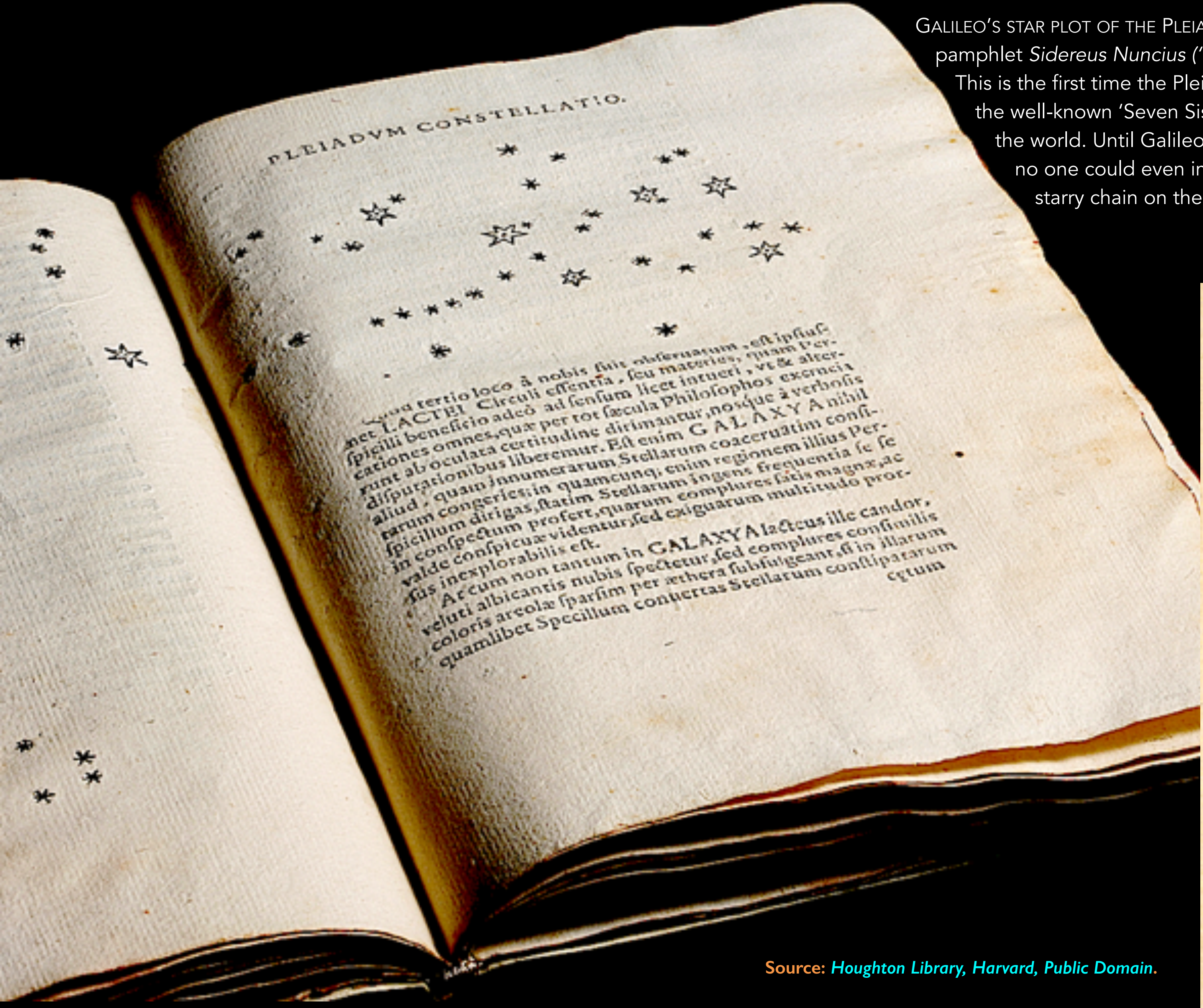
Hildegard's only musical and intellectual counterpart in her time was another nun, named Kassia (also Kassiani), who composed similarly tradition-shattering hymns in her homeland, Byzantium, home of Greek Orthodox Christianity. These two women bookend the music of their time in much the same way Cecilia Payne and Vera Rubin bookend modern astronomy as we revere it today.

Sometimes it is good to dream about something besides stars.



Fishing at the Pont de Clichy (Asnieres), Vincent Van Gogh, 1887

On the other hand, look what happens when we dream about stars.

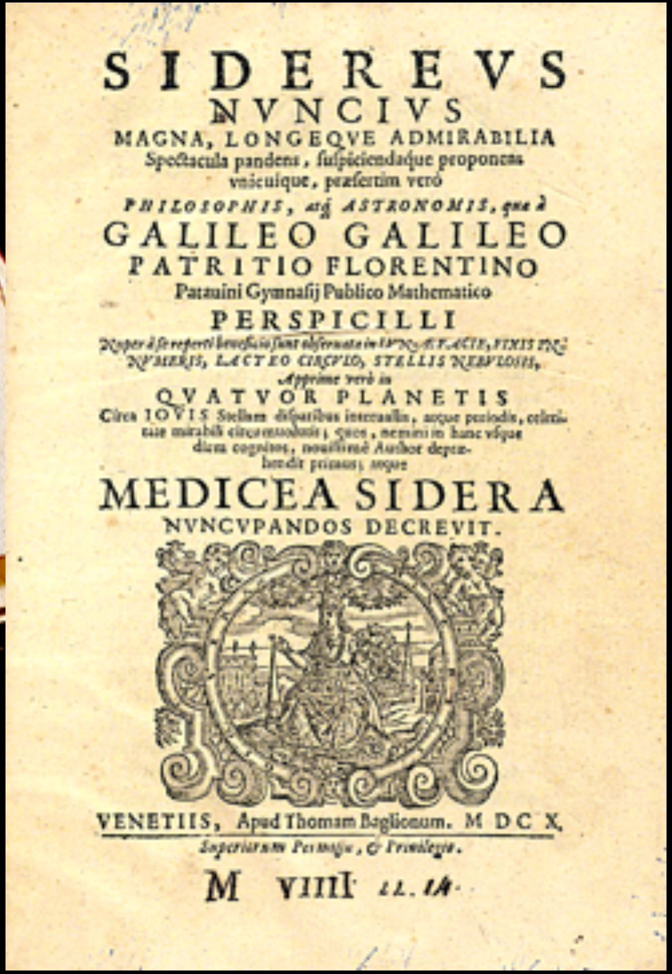


PLEIADVM CONSTELLATIO.

Quod tertio loco à nobis fuit obſeruatum, eſt ipſiuſmet LACTEI Circuli eſſentia, ſeu materies, quam Perſpicilli beneficio adeò ad ſenſum licet intueri, vt & altercationes omnes, quæ per tot ſæcula Philoſophos excruciarunt ab oculata certitudine dirimantur, noſque à verboſis diſputationibus liberemur. Eſt enim GALAXYA nihil aliud, quam innumerarum Stellarum coaceruatim conſitarum congeries; in quamcunq; enim regionem illius Perſpicillum dirigas, ſtatim Stellarum ingens frequentia ſe ſe in conſpectum profert, quarum complures ſatis magnæ, ac valde conſpicuæ videntur; ſed exiguarum multitudo prorſus inexplorabilis eſt.

At cum non tantum in GALAXYA lacteus ille candor, veluti albicantis nubis ſpectetur, ſed complures conſimilis coloris areolæ ſparſim per æthera ſubfulgeant, ſi in illarum quamlibet Specillum conuertas Stellarum conſtipatarum cœtum

Galileo's star plot of the Pleiades from his March 1610 pamphlet *Sidereus Nuncius ('Sidereal Messenger")*. This is the first time the Pleiades stars fainter than the well-known 'Seven Sisters' was revealed to the world. Until Galileo's 30 power telescope, no one could even imagine the distinctive starry chain on the left side of the cluster.



SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, ſuſpiciendaque proponens
vnicuique, præſertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnaſij Publico Mathematico
PERSPICILLI
Nuper à ſe reperti beneficio ſunt obſeruata in LVNÆ FACIE, FIXIS INNVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam diſparibus interuallis, atque periodis, celeritate mirabili circumuolutis; quos, nemini in hanc vſque
diem cognitos, nouiſſimè Author depræhendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permiſſu, & Priuilegio.

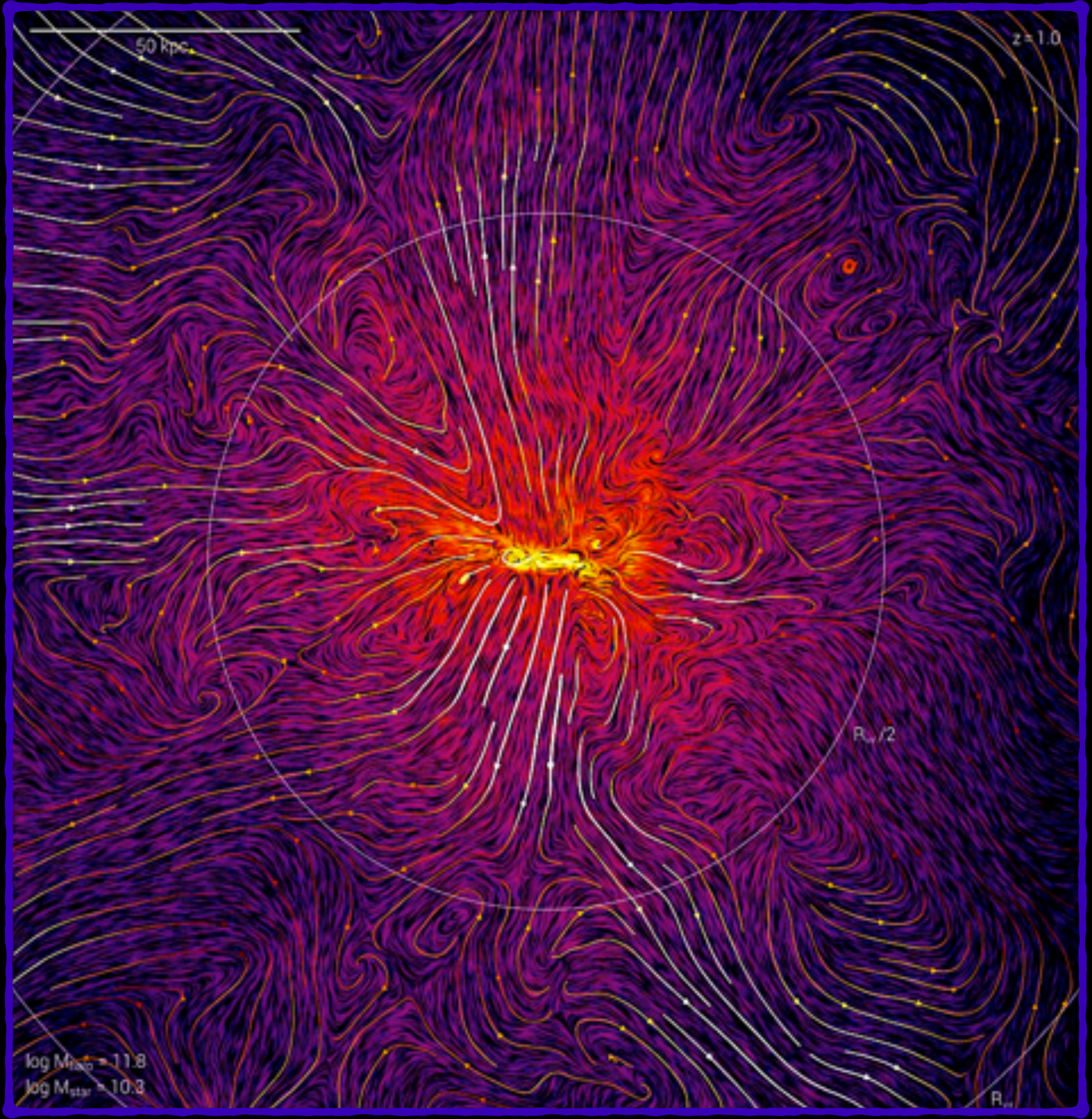
M VIIII ll. 14

Source: *Houghton Library, Harvard, Public Domain.*

Let’s visit the Palomar Hale Telescope and ask . . .

And while we’re at it, let’s see what it is like to stay overnight.

How do galaxies breathe?



WHERE DO GALAXIES GET THEIR GAS, AND WHAT DO THEY DO WITH IT?

If a picture is worth a thousand words, the image to the left is worth a thousand equations. The original image caption reads, 'The topology of halo-scale gas flows around a single TNG50 system, similar in mass to a Lyman-break galaxy. Streamlines of gas motion are overlaid on a line-integral convolution image of gas density modulated by its velocity field. Outflows emerge collimated from the central galaxy traverse half the virial radius (dotted circle), producing small-scale vortical motions as well as a large-scale, circulatory, galactic-fountain type flow confined within the halo virial radius.' *Illustris TNG 50.*

That's one way of explaining it. Let's break that down. The Cosmic Web comprises a great number of filamentary structures that flow into large cores (aka nodes) that are multiple galaxy clusters that have swirled into each other over the last 10 billion years. The result is a galaxy supercluster. Most of the galaxies are elliptical and have no star-forming gas left. Superclusters are so massive they pull in vast quantities of primordial gas left over from the beginning of the universe. The inflowing gas does not tumble in from all sides, but rather via immense, long filaments whose gravity pulls in gas from cosmic voids. This gas is very cold—perfect for forging new galaxies. That is why cosmic filaments are birthplaces of spiral galaxies while supercluster are retirement homes for ellipticals. Most of the spirals align so their rotating discs line up with the gas flowing down the dense tubular cores of the filaments. Hence the inflowing gas enters the spiral galaxies via their disc planes. (The video below shows how it works.) Once inside the galaxy disc the gas naturally forms stars, many of which expire rather noisily as supernovae. On average a spiral galaxy can experience 25 to 45 supernovae every million years. The supernovae blow the gas upward and out of the galaxy back into deep space. One can think of this cycle as a galaxy's breathing cycle. The full story is much more complex, as suggested by the flow diagram to the left. The critical fact for a spiral galaxy is that it will retain its star-forming youth only as long as gas flows in along the filament. If that stops, the galaxy runs out of gas.

Watch the full-cycle video here.
Source: ARC Centre for All-Sky Astrophysics.

How do astronomers make sense out of this mess like this?

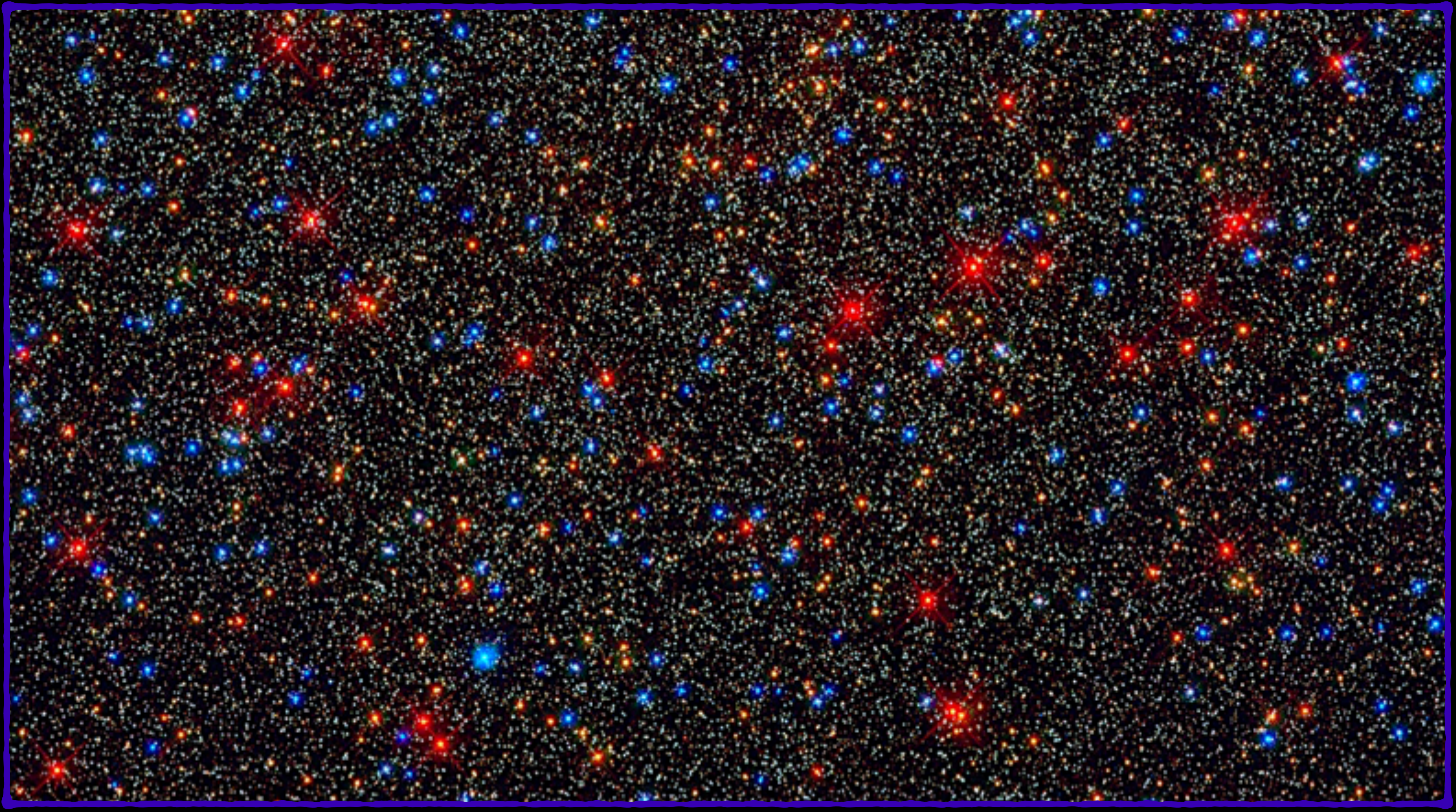
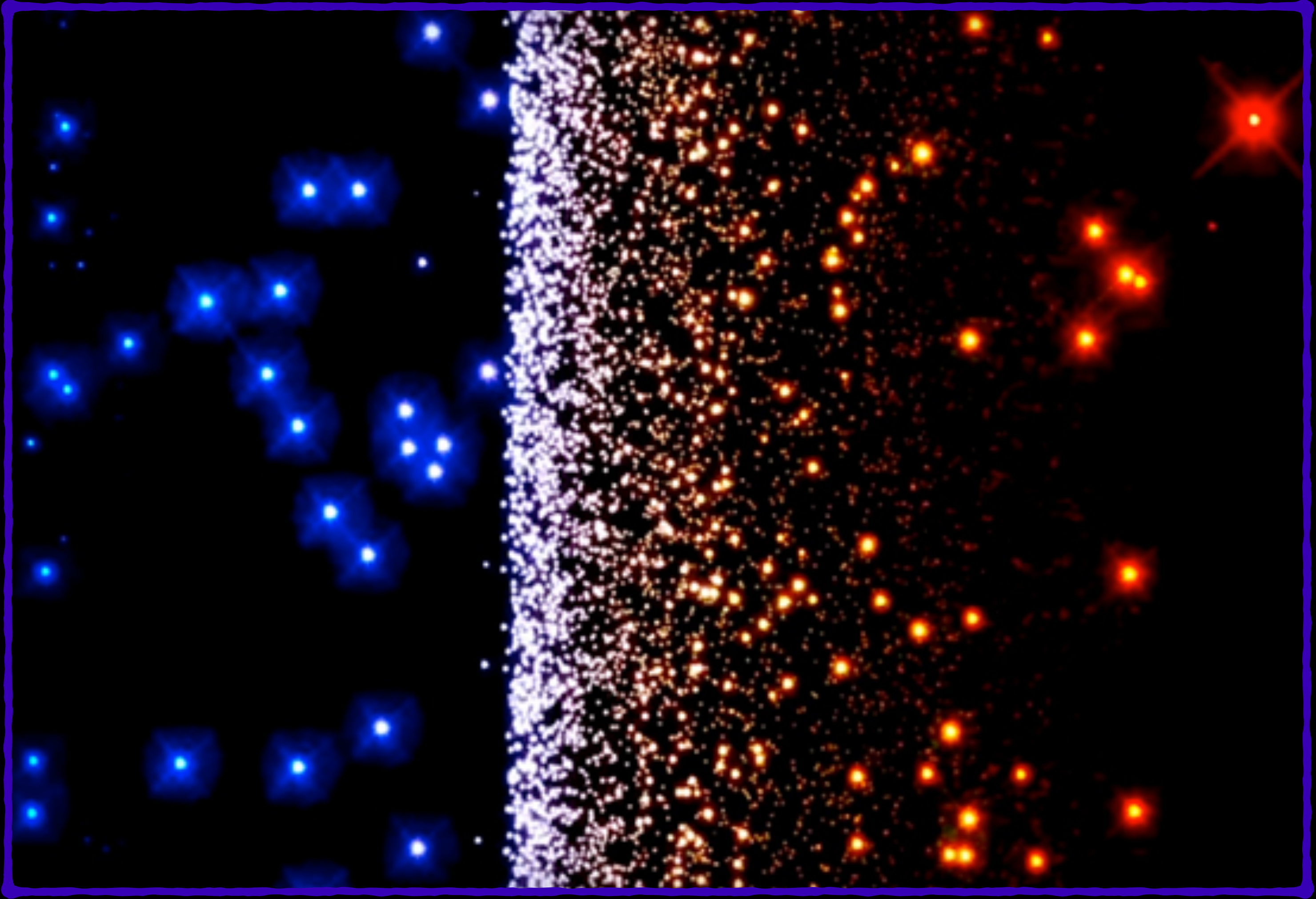


Image of the central region of the Omega Centauri dwarf galaxy core acquired by the Hubble Space telescope. The resolution of the Hubble is so good that we can see through it clustered stars to the vast emptiness of space beyond.

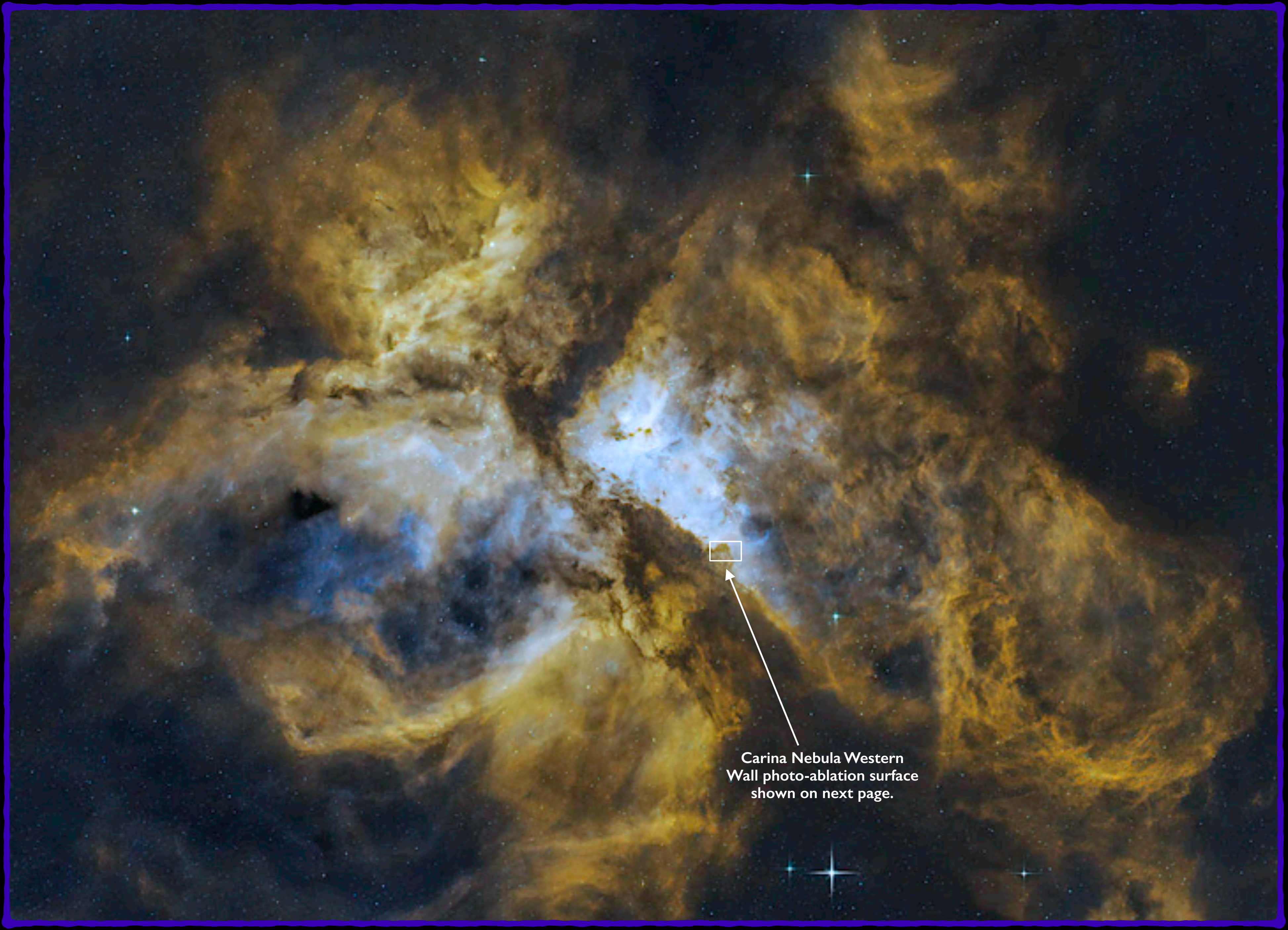
Watch how astronomers convert a picture of stars in the sky to information about the size, age, and life span of stars in a cluster.

THE GIANT BALL OF STARS in southern skies named Omega Centauri has long been called a globular cluster. But the presence of multiple populations of stars within it and its enormous mass of at least 10 million stars has long been suspected to be the core of an ancient dwarf galaxy that was accreted (the astronomer's polite way of saying shredded to bits) in a long-ago series of sideswipes that transferred the dwarf's disc stars to the Milky Way, mostly in its vast spherical halo. The ancient core was too dense to let that happen, and today soldiers on as Omega Centauri. Amateur astronomers consider it one of the great showcases of the sky because no matter what size telescope you have, it glitters with myriads of pinpoint stars, reminiscent of what a disco ball would look like if all its mirrors were half a millimetre square lit by a giant laser.

There are a number of ways to sort out the truth of an astronomical object's ancestry. One of them is its colour-magnitude diagram, aka CMD. As we look at the above image we see plenty of bright blue and red stars mixed in with the white specks. Those represent individual stars of specific mass range, which largely determines their colour and age. Around 1910 a Dane named Ejnar Hertzsprung and an American named Henry Norris Russell thought of a way to translate a 3-D field of stars into a 2-D diagram that classified them by brightness and colour—blue for hot and red for cool. It turned out that the white stars (like our Sun) did not line up vertically as in this image, but rather along a sloping line rising upward to the left. To see the full-motion transition between stars in the sky to CMD on a page, watch this video.



How do clouds of creation



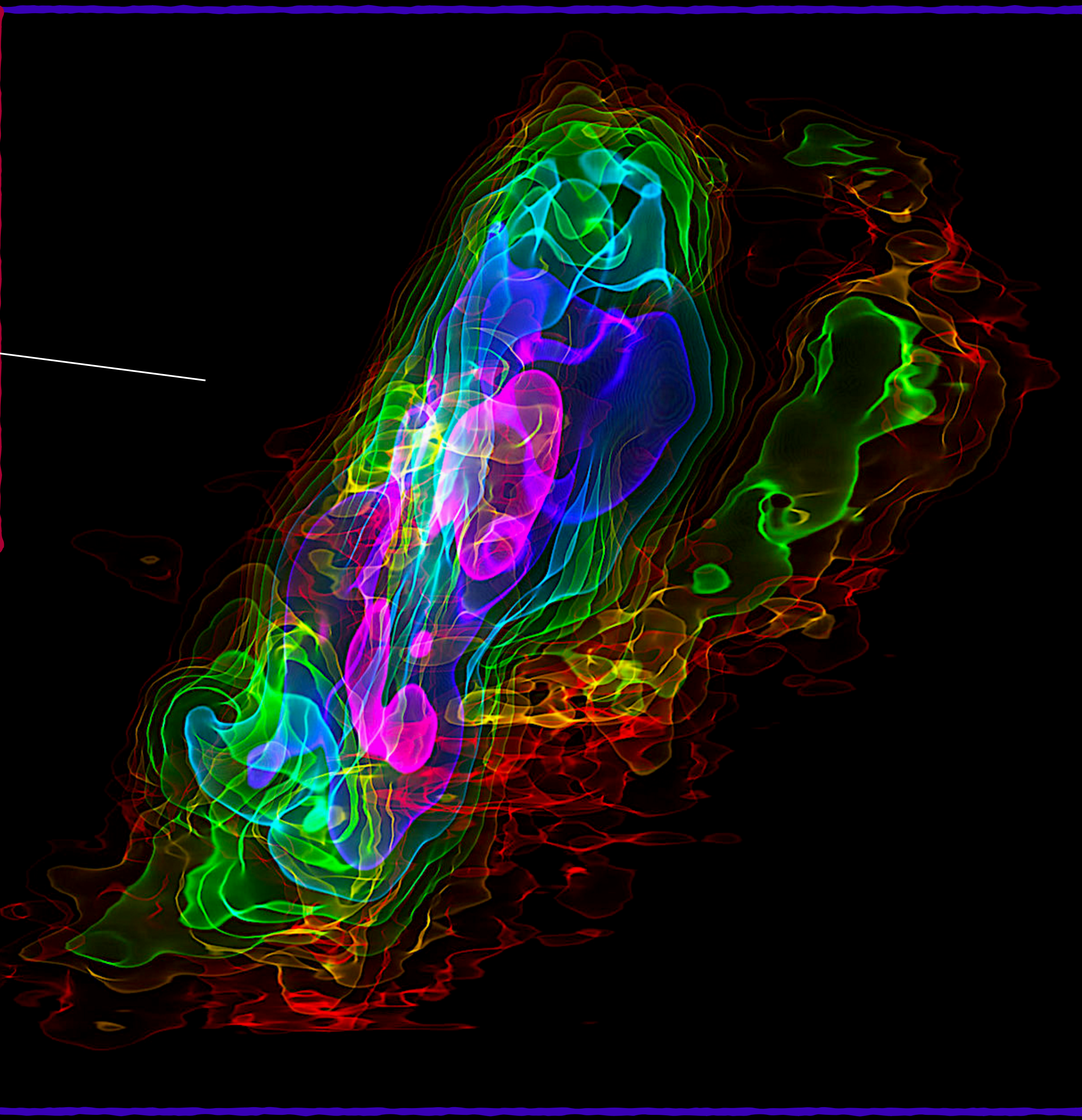
Carina Nebula Western Wall photo-ablation surface shown on next page.

become clouds of destruction?

THE RELENTLESSLY EROSIVE EFFECTS of photo-ablation from high-energy UV radiation vividly reveal themselves in this five light-year (50 trillion km) section of the Western Wall in the Carina Nebula. The hillocky terrain of the Western Wall density occlusion comprises multiple pimple-like domes compressed by multiple turbulent shocks and searing stellar winds. The bright reddish surfaces on darker gas/dust pockets reveal high-energy photons sputtering atoms off dust particle surfaces and HII and H_1 atomic hydrogen gas ionising into electrons and protons. The smeary look to dusty gas that appears to be dripping off the right edge of the cloud suggests low-velocity wind shear. The visual resemblance between earthy and celestial clouds is more than merely analogous: the same physical laws apply to bodies of gas despite vast differences in density and the volumes they occupy. The crisp resolution in this image is due to the adaptive optics system on the Gemini South 8.1 metre telescope atop Cerro Pachón in Chile. (*Watch their video here*.)

What is life like in the middle of a galaxy?

Everyone knows NGC 253 in Sculptor—or at least we think we do. But does it conceal secrets behind that mottled surface that we all see and image so well in our telescopes? What does NGC 253 look like if we examine a contour map of its carbon monoxide (CO) gas? CO is a well-known tracer of neutral hydrogen gas—the simplest of all atoms. Atomic hydrogen is the raw material of star formation, but radiates very little energy on its own and is therefore hard to quantify. However, simple H_I gas is often associated with CO gas clouds which radiate electromagnetic energy in the far infrared and microwave bands. The H_I-to-CO ratio is about 10,000 to 1. The map to the right shows the contours of CO gas concentrations in NGC 253, and thus the reservoirs of hydrogen gas available for star formation there. Blue is low density (<1000 atoms per cc) and pink is high density (>10,000 atoms / cc). The box superimposed on the galaxy shows where the image is located in the galaxy. The densest hydrogen is in the middle of the galaxy, which should translate to abundant star formation there. But it doesn't. The star formation rate (SFR) or NGC 253 is roughly 3 new stars per year (the Milky Way SFR is between 1 and 2). Given the densities of hydrogen gas in NGC 253, it should be forming 3 to 5 times as many stars as it does. So what is stopping it ('quenching' in astro-speak)?

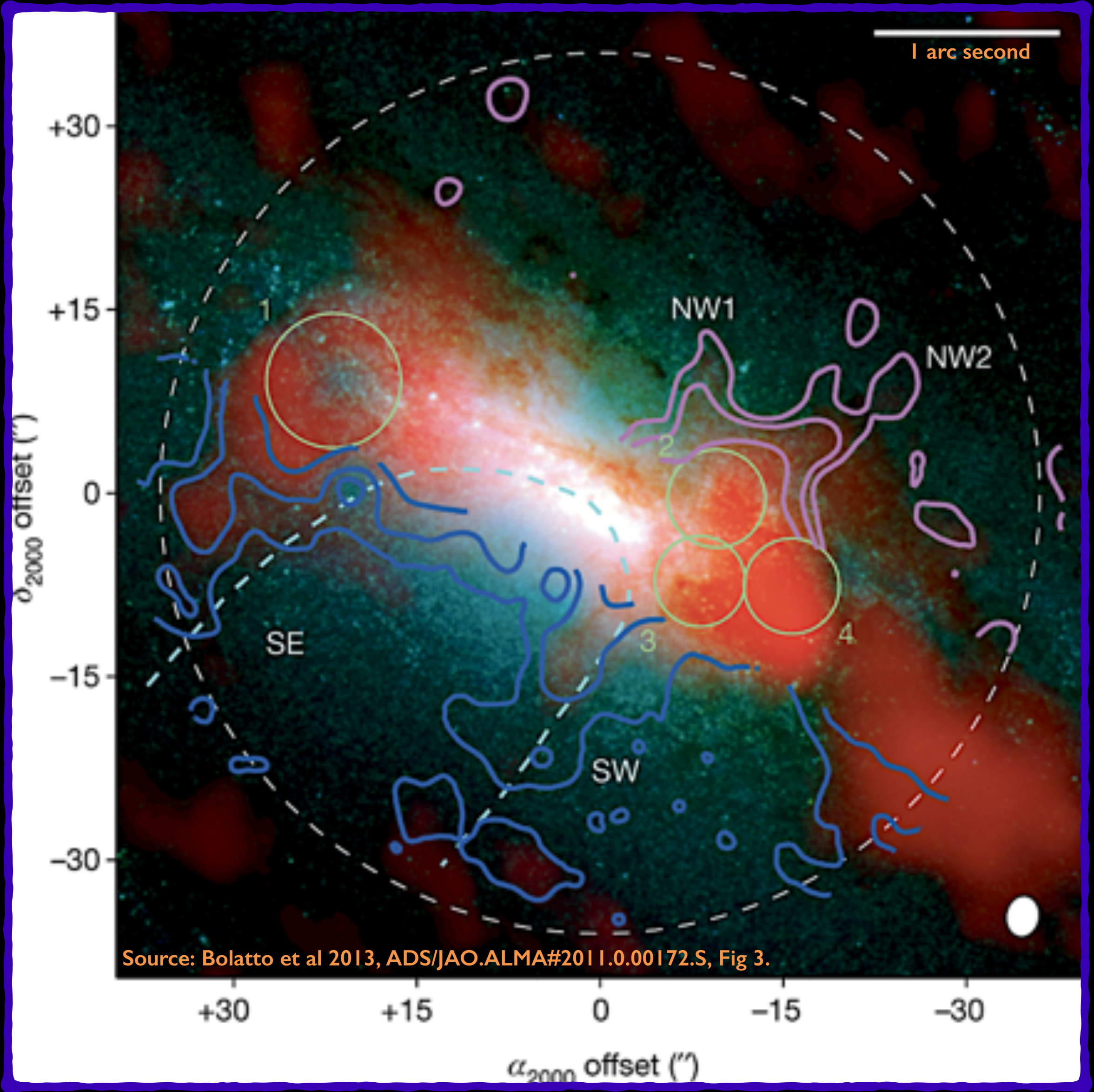


Source: Bolatto et al 2013, *Suppression of star formation in the galaxy NGC 253*. Nature 499(7459):450-3. Original image: *ALMA (ESO/NAOJ/NRAO)/Erik Rosolowsky*.

Galaxies tend to be their own worst friends. They self-regulate to the point where no matter how near or far we look, they tend to fall into fairly narrowly defined ranges of mass—we don't see very many eenie tiny spirals, nor do we see huge sprawling things a dozen times the size of the Milky Way or Andromeda. Conversely, we do see a significant size (and therefore mass) range in elliptical galaxies. That's because elliptical galaxies started off as multiple spiral galaxies that collided with each other so often that they have settled into a giant bee swarm bereft of any hydrogen to make new stars. Ellipticals range from tiny, ancient dwarf galaxies with a few million stars to behemoths such as M87 in Virgo at multi-trillions of solar masses. The one thing all have in common is they have no gas left to form stars—they are literally 'red and dead'.

So those beautiful swirly lines in the first image are a portrait of life in a rather tough, riot-prone neighbourhood. In fact, the mottled visual image of NGC 253 suggests that the galaxy has a good many dense dark dust clouds mixed in with bright clumps of star-forming clouds. This is a hallmark of galaxies forming large numbers of large star clusters. Those bright clouds are tempestuous places to live. They are chockablock with shock waves from young stars and supernovae, searing UV light that tears molecules to shreds, and gas so energetically hot that it tends to burst outwards in the form of gravity-mediated explosions known as massive gas flows. The placid regions of cold hydrogen and cool molecular gas get pushed in front of the expanding shock waves, to the point where they are ejected from the galaxy altogether at speeds of dozens to hundreds of kilometres per second. The depletion of so much hydrogen gas has a disastrous effect on the ability of the galaxy to form new stars. That is why NGC 253 is forming only one-third to one-ninth the number of stars that its gas reservoirs say it can.

To the right we see the results of NGC 253's multiple starburst clusters hurling out gas at high velocities. The green circles are known starburst regions (largely hidden from our direct view by dense galactic dust). The pink contours above the galaxy show two outflow regions erupting from the starbursts near the galaxy's core; they are reddish to indicate that they are red-shifted away from the galaxy centre. The multiple blue contours show at least three massive gas outflows ejected in our direction, hence are blue-shifted. All that gas ejected at high velocities out of the galaxy depletes the available gas in the galaxy's central regions. The destructive effects are largely confined to the central regions because those are where the available gas pressures are high enough to form energetic supermassive young clusters.



Source: Bolatto et al 2013, ADS/JAO.ALMA#2011.0.00172.S, Fig 3.

Beyond the central region roughly within the white box above, star formation in the spiral arms approximates that which we find in run-of-the-mill spirals like our own Milky Way and Andromeda. Just how long NGC 253 can continue at this rate depends on the amount of ejected gas that eventually returns plus the inflow of pristine gas along the cosmic filament in which our Local Group and nearly all the galaxies in the 30 Mpc Local Sheet reside. Given what we know thus far, NGC 253 may end up as a gas depleted ageing-star spiral of the SO or lenticular type.

Further reading: *Levy et al 2020*, *Walter et al 2017*, *Leroy et al 2014*.

Why don't I see the familiar face hiding in all this hair?

Is this vibrantly hued mess the same Pleiades star cluster known to every school child as the 'Seven Sisters'?

Well, not exactly. The optical-band light from the several hundred stars that make up the famed asterism were intentionally suppressed in this image by Francesco Antonucci, the astronomer who recorded and processed this plate. (The stars we do see here are not part of the Pleiades cluster; they are field stars on the near and far sides.)

Suppressing only the Pleiades stars when processing this picture enabled Antonucci to concentrate on the intricate lacework of dusty filaments that lies behind the Pleiades. The Pleiades stars have relatively little dust of their own. The dust clouds that are moving behind the Pleiades are part of an enormous molecular cloud dozens of times as massive and many times larger than the Pleiades.

Dust-riddled molecular clouds delight astronomers no end. They are the birthplaces of stars. Without any dust in a molecular cloud there would be no stars in the sky at night, no sun (a star, after all), and of course, no us.

Molecular clouds contain vast amounts of the stuff—5% to 20% by mass, though only a few thousandths of a percent by volume. The tiny sooty carbon or flinty silicon/sulphur/iron dust particles contain all the atomic elements that appear here on Earth. Plain old H_2O water, for example, coats the surfaces of most sooty carbon dust particles so other atoms and molecules adhere to it. Without water, stars wouldn't exist, either.

But it is the silicon-rich particles that intrigued Francesco Antonucci. Many silicious particles are dipolar, they have magnetic poles. Hence they align with local magnetic fields, as we see so vividly here in all that wavy hair. The partly chaotic and partly coherent filaments here indicate the degree of shock turbulence in the dust behind the Pleiades. The colours are artificial, but use the same palette we associate with warm (red) and cool (blue). The yellow-green is in between. The magnetic field lines frozen into the gas/dust cloud behind the Pleiades cluster suggest that the far-off cloud is lumpily collecting itself together, in many *many* millions of years might infall into a new star cluster—just like the Pleiades did 106 million years ago.

The reason Frencesco Antonucci was so interested in the passing cloud's magnetic fields becomes more apparent in this wide view of the region between the Pleiades (blue cluster top) and the California Nebula (red vertical smear bottom centre). Magnetic fields tend to do two things in a complex gas/dust/stars region like this. First, they align silicious dust particles into linear filaments that trace the magnetic field lines. This is readily apparent in the linear streaks in the California Nebula and several other regions in this image.

The second function of magnetic fields is that they are part of the tripartite interaction between the divisive properties of turbulent shock waves, the aggregative property of gravitational fields, and magnetic fields as the tempering mechanism between the two. Star formation begins millions of years prior to the appearance of any stars. Brutally cold clouds of molecular hydrogen collapse out of originally diaphanous, pristine clouds of neutral hydrogen and dust very tenuously bound by their own gravity. A galaxy is occupied in part by veritable multitudes of atomic hydrogen clouds that rotate benignly around a galaxy's disc along with the stars. However, can be triggered into collapsing as they enter into the ponderous, elephantine, lumbering spiral arms of the galaxy, which are, after all, density waves.

As dust clouds collapse, the dust tends to gravitate toward the centre. Dust absorbs energetic starlight that would otherwise go into warming up the gas atoms, keeping them at energy levels that are brutally cold to us but warm by galaxy standards—50 to 100 degrees Kelvin (above absolute zero). With dust absorbing starlight, the atoms can cool, all the way down to a few degrees above absolute zero. Under these conditions, two atoms of hydrogen can couple and become molecular hydrogen. Only molecular hydrogen can make stars because its binding energy can take extreme heat whereas atomic hydrogen ionises at 3000 to 6000 K.

The end result is a fairly rapid mass collapse into clumps which become dense enough to form star clusters. When a star cluster first forms, the inward pull of gravity is resisted by turbulent shock waves that are ubiquitous in spiral arms. Nearly all those lens-shaped structures in the picture are the compressed gas and dust on the front surface of a shock wave. Shock waves are hugely divisive—just like ocean waves that interact in many sizes and shapes. But now, all those electrons that were freed when molecular hydrogen was made can race throughout the region. They are harnessed by magnetic fields into powerful bands of electromagnetic strength that slowly weaken the shock waves until gravity can eventually take over to collapse molecular clouds into brilliant star clusters like the Pleiades.

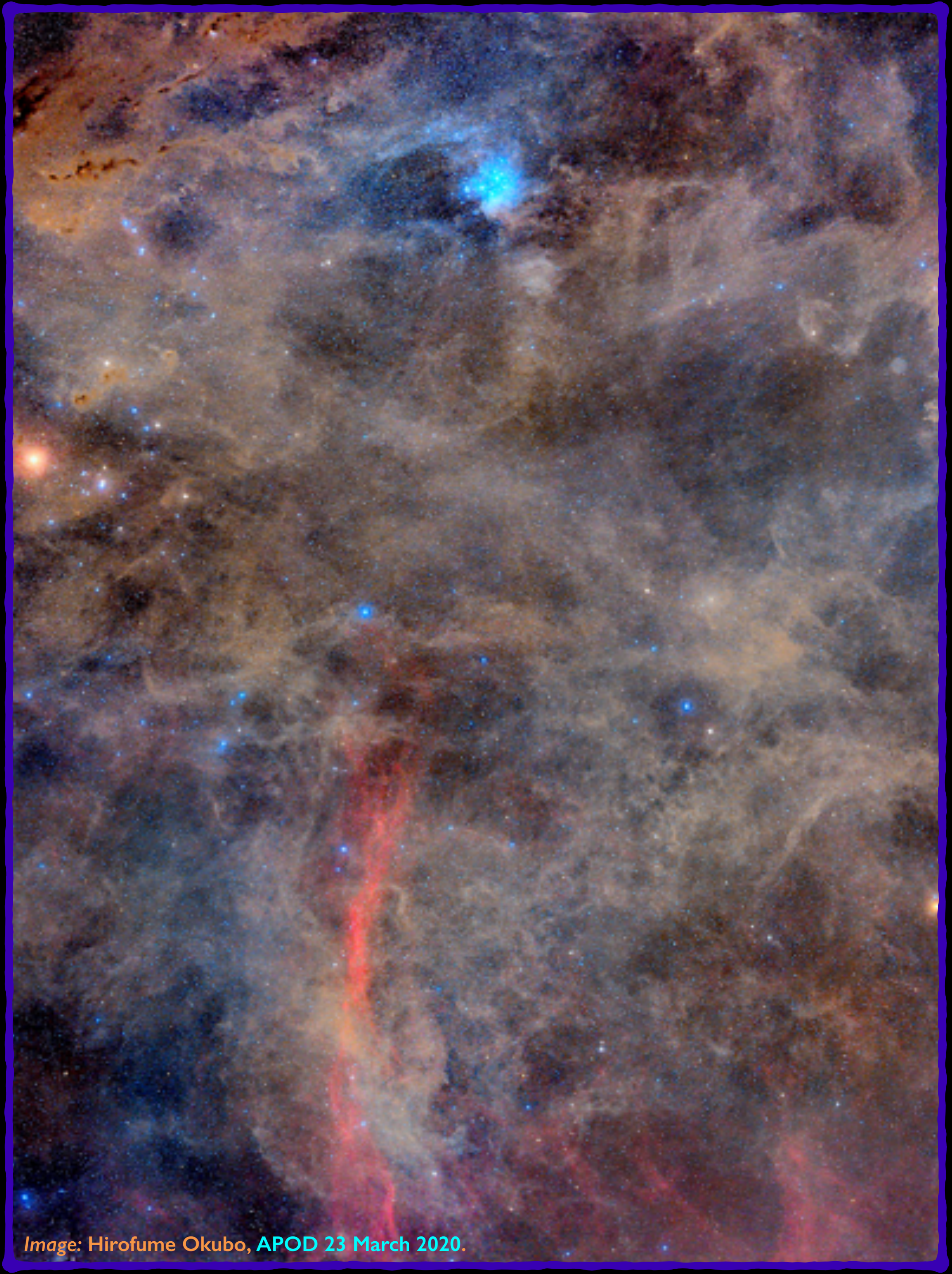
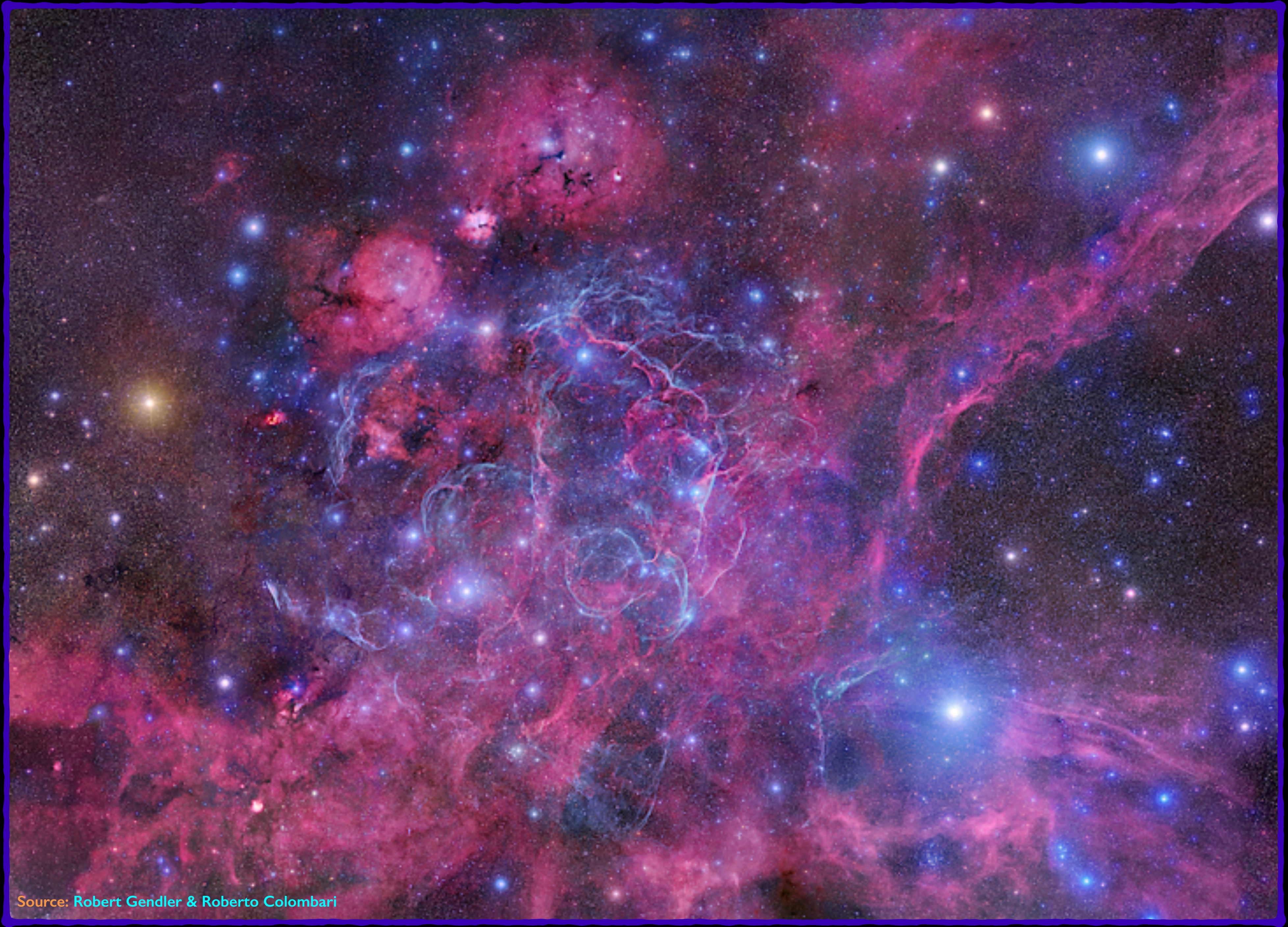


Image: Hirofume Okubo, APOD 23 March 2020.

Why is the VELA supernova remnant so twisty?



Source: Robert Gendler & Roberto Colombari

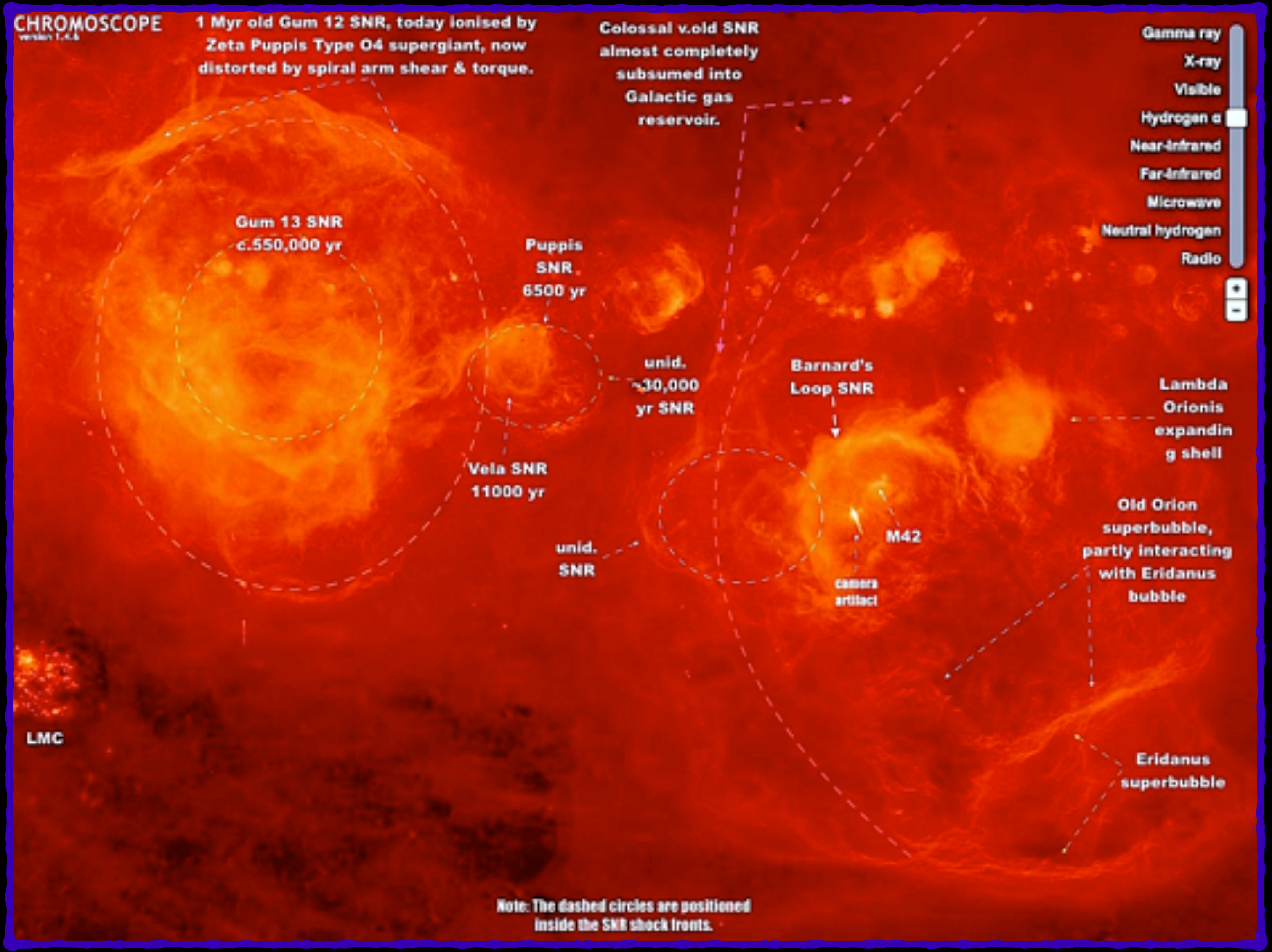
At 11,000 years old, the Vela supernova remnant is only the latest in a long history of supernova remnants (SNR) that have occurred in this small corner of the sky in the last 3 million years

The constellation Vela sails above Carina, whose hull floats on the Milky Way. When we look naked eye toward those sails we see sparkling mattes of stars. Invisible to us are incandescent red gas and dust-laden shock waves that will one day be more stars to see. This image covers a huge area—from the Large Magellanic Cloud (LMC) to well beyond the Orion Nebular Complex and Barnard's Loop mid-right. The complex's intertwined layers of red hydrogen alpha emission record the fiery deaths of massive stars. The community elder is Vela's Gum 12 that ejected its great shell of arcs over a million years ago.

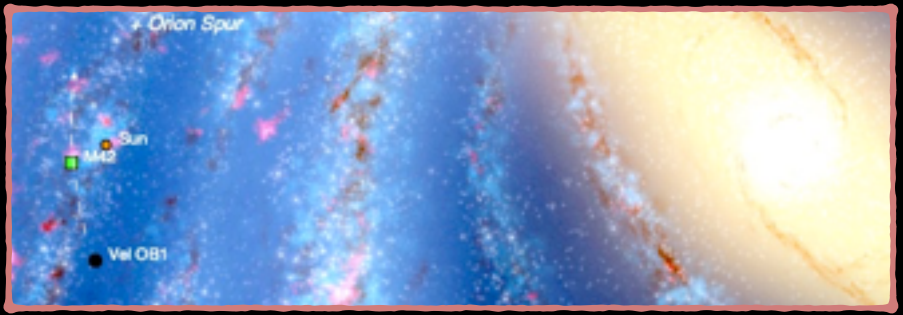
The Vela SNR is part of the Vela OB1 Association of stars. The Association formed hundreds to thousands of stars 14,000 to 16,000 years ago as the final stage of a cluster-making process than began over four million years ago. In contrast, the M42 Orion Nebula star-formation history started only about 300,000 years ago and is a long way from witnessing its first supernova.

Molecular clouds, like stars and gas nebulae, rotate around the Galaxy in a circle (arrow in the drawing to the left). As the clouds enter into the dense spiral arms at an angle, they are subject to wrenching shear and torque forces that initiate star formation in very large numbers.

The portrait to the right shows a million years in the life of a spiral arm. To see what it looks like speeded-up, *watch this video*.



Above: Note how two colliding superbubbles such as the Orion and Eridanus bubbles tend to flatten at their contact interface. This occurs because the gas/dust that the expanding supernova shells have compressed in front on them as they expand now respond to their accumulated gravitational binding energy and the dynamics of interacting shock waves. *Source:* Chromoscope, University of Durham, U.K.



Left: Despite the seeming chaos of this image, it is simply astrophysics following the laws of electromagnetism, thermodynamics, Mach speed, and gas dynamics. Boringly predictable, but also spectacularly beautiful.

What happens in the middle of a nebula like the Rosette?

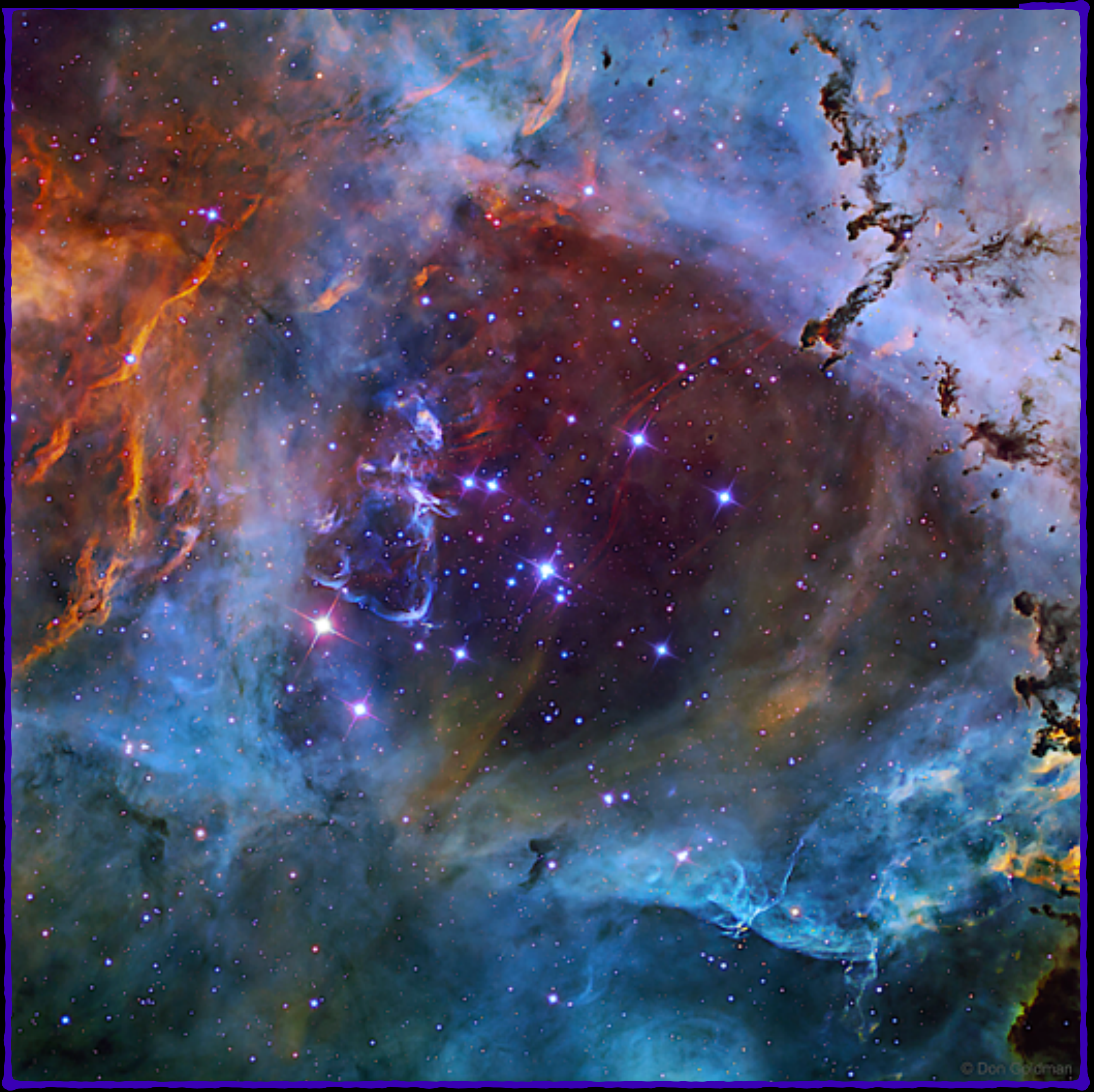
Star cluster NGC 2244

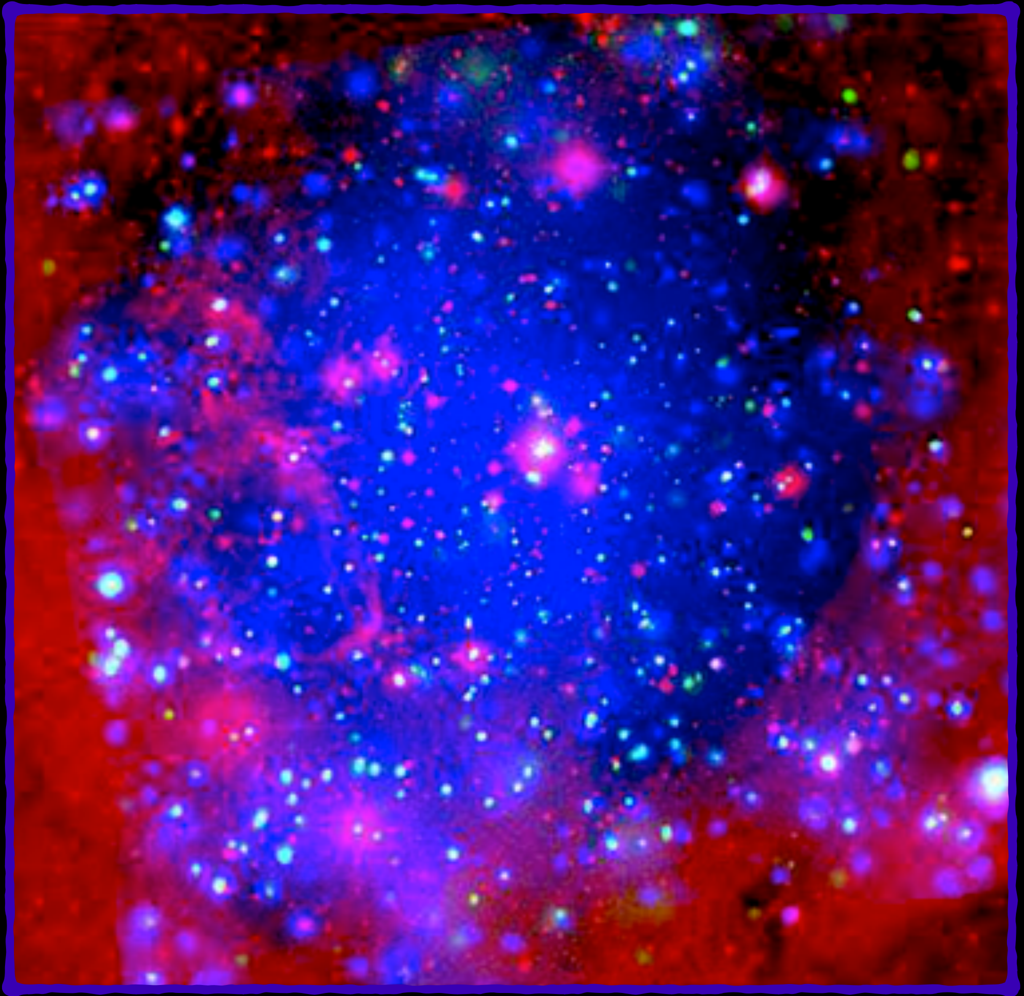
How many times have we looked at the endless array of astronomy images of the full-diameter Rosette Nebula in Monocerous and marvelled at the beauties of its gas shell and those twisty dark filaments, without paying all that much attention to the stars that cause all this?

In this image by Don Goldman we see the rich variation in stars that create the energy which lights up the outskirts, clears the gas from the centre, and will eventually eject all this tracery into the 10,000 K warm chemistry lab of the interstellar medium. Many future generations of stars will be made from this gas. Star formation efficiency within giant molecular clouds is only about 1% to 5%. Each generation of stars will have a more complex chemical mix as the interstellar medium is enriched by the new elements forged in any given cluster. One after another, each adds its own bits. Expelling their birth gas in as necessary to a star cluster as shedding skin is to a snake.

The glittery stars in the centre of this image are a young cluster of around 2000 stars whose widely varying masses were ordained by the densities of gas, magnetic fields, and gravity that control the making of a star cluster across a typical cluster formation span of a million years.

Yet it is the stars we *don't* see that make NGC 2244 such an interesting study. What are they, where are they, and why are they invisible to our eyes and optical-band astro-images?





When we look at images of the the two million year old star cluster NGC 2244 in optical band light, we can spot perhaps 50 stars in the hollowed-out central hole of the cluster. The hole signifies that the cluster has initiated its gas-clearance cycle, which will hurl its unused gas back into the nearby spiral arm. What we do not see are more than 900 X-ray sources that are very young stars up to 100,000 times brighter in the X-ray band than in the visual. This Chandra satellite image reveals these stars for the first time. Of these, some 77% were also detected by the FLAMINGOS near-infrared (NIR) project that catalogues previously unknown young members of clusters like NGC 2244. If we are to fully understand the dynamics that make a star cluster and predict its future, we first have to know its SFR or Star Formation Rate—how many stars it actually has, what kind, and when they formed in relation to the rest. For every optically visible star there may be many other stars that emit only in X-ray and infrared bands. Very young stars go through a brief phase called the T Tauri stage in which they emit most of their light in X-rays. The X-rays are produced by magnetic reconnection of field lines broken by the chaotic turbulence of he star's interior and the high rate of gas infall onto its surface. A census of the X-ray population helps us calculate the cluster's age and its probable total mass. In this X-ray satellite image the overall blue colour comes from soft (0.5–2 keV) X-ray emission. The green intensity is scaled to the hard (2–7 keV) X-ray emission. The bright dots are T-Tauri stars that were previously unknown. *Source: Wang et al 2007*.

These beautiful filaments and clumps look cold and dark, but infrared observations reveal them to be the wombs of unborn stars. The filaments are leftovers after the star cluster's rapid initial collapse into the stars we see as NGC 2244. For over a million years they remained cold dark blobs in the outskirts, lightly bound by their own gravity but too low-mass to initiate collapse into stars on their own. The ignition of the hot young protostars in the left-side image has now supplied enough radiation energy to compress these clouds' surfaces, overcoming their feeble internal pressure to initiate collapse into stars. That this stage is now underway in these blobs has been confirmed by infrared photometry. Infrared observations, like the X-ray images opposite, require that the detectors must be beyond the earth's atmosphere, which absorbs radiation in the key window between 20µm to 850µm. Hence the high budgets allocated to designing and lofting the satellites like XMM Newton and Spitzer which were specifically designed to record X-ray and infrared radiation respectively. Not all of these blobs will achieve the critical density that initiates gravitational collapse. Most will become brown dwarfs only 13 to 80 times as massive as Jupiter, warm enough to fuse deuterium (^2H) or, in the more massive ($> 65\ M_J$) lithium (^7Li) which is detected by the presence of a 670.8 nm emission line in a spectrogram. The study of brown dwarfs is a complex one, but well worth the read. *Image source:* ESO *potw1847a,* Nov 2018 acquired with the FORS 2 camera on the VLT in Chile's Atacama Desert.

Why are planetary nebulae so messy?

What explains the unusual striations in Planetary Nebula StDt56 in Triangulum, near M33?

Planetary nebulae are the lasts gasps of a dying AGB red giant. As its core of carbon and oxygen atoms squeeze into a tiny ultra-dense ball called a white dwarf, its gravitational energy can no longer retain the massive layers of gas in its envelope. In response the envelope expands into the vacuous interstellar medium around it. The 'Eye of God' annulus of M57 in Lyra and the Helix Nebula in Aquarius give the impression of being a ring with a star in the middle. That is an illusion caused by our viewing them almost directly down their polar axes. In reality, planetary nebula gases expand outward in an impressive array of hard-to-explain shapes whose causes include magnetic fields, how fast the original star was rotating, shock waves in the expanding gas, and the unpredictable gas/dust densities into which they are expanding.

StDr 56 was discovered by amateur astronomers Marcel Drechsler and Xavier Strottner, who are members of a very small club of planetary enthusiasts who comb through surveys of the sky looking for undiscovered planetary nebulae. In this image, we do not gaze down the polar axis of the nebula, we are looking at it almost equatorially. The slight protrusions at the north and south poles suggest that we were looking at it from above its equator.

Untangling the effects to get at the cause is an endless problem in astrophysics. The analyst's best friend is numbers—the more objects of similar kind that one has, the easier it is to weed out false leads. But StDr 56 has very few analogues out there—HDW2 (next page) and Kronberger 63 come to mind, but they, too, are vexingly faint. It doesn't help that they are so recently discovered (by so-called amateur astronomers, yet–oh dear!) they haven't attracted the hearts and wallets of grant giving organisations.

Strottner-Drechsler 56 (StDr56) Goblet of Fire Nebula

What cause StDr56's inexplicable striations? The nebula is not rotating rapidly like Jupiter. In fact, the nebula is not rotating at all. Instead, its energy goes into expansion.

The first thing to note is those long thick filaments. Filaments this contiguous with respect to the overall size of the planetary are very unusual for a PN, and rather hard to explain. Such striping can occur when the gas flows along magnetic field lines. A white dwarf can indeed have a strong magnetic field, but it is doubtful that the original star's magnetic field was so powerful it could shape gas structures of this size.

In the image, the red emission is hydrogen-alpha, signifying that the outer hydrogen envelope of the star was ejected first and is now cooling. The bluish colour comes from doubly ionised oxygen (perversely shortened to O-III) that originated deep inside the star near the old core, now a white dwarf. Both H-alpha and O-III glow strongly from the energetic ultraviolet (UV) light from the central star—whose surface may sear the sky with 100 million degrees K radiation at the surface. If the oxygen layers seem smaller and interior to the hydrogen layers, that is because the oxygen originated very near the centre of the star and was likely dredged up from the star's surface by giant convection cells that are common in the last stages of an AGB star's life just before it becomes a full-fledged planetary.

StDr56's apparent size on the sky is nearly the same size as the full Moon. Drechsler and Strottner identified a star named Gaia DR2 300394067131824768 as a candidate for the nebula's central star. It is about 1,130 light years from Earth. That would make the nebula about 10 light years across. That is suspiciously large for a planetary and raises the question of what, exactly, could push the gas so far away so fast.

Can we answer that question by carefully measuring the properties of the nebula? Well, yes … and no. The layers we see are the shells of gas from inside the star before the star exploded. When the white dwarf compressed into a superheated ball, the thick layers of helium, traces of beryllium, boron, carbon, and nitrogen expanded unevenly, mixing the gases. These were shaped into distinctive patterns by the star's magnetic field. Measurements of the Doppler velocity for the gas suggest that the outermost hydrogen layer must have been accelerated almost explosively for it to reach the diameter that it presently has. Further inward, each layer of progressively heavier elements wasn't accelerated as much due to their heavier mass. If the dying star was massive enough, say 5 to 7 times the Sun's mass, then it might have enough energy to generate such a rapid wind into space.

StDr 56 is in the constellation of Triangulum, about 30° above the plane of the Milky Way. The nebula's distance of ~1130 light years puts it in the very upper reaches of the Galactic disc—not a region that typically produces planetaries. Space is a near vacuum that far from the dense environs of the Galactic disc. StDr 56 would expand with virtually no dust to offer resistance, which can explain its anomalous size—and possibly those striations.

StDr56 is vexingly faint. The above image was acquired by astrophotographer Robert Pölz in Austria using a 25-centimetre telescope. The image required a boggling 60 hours of exposure time. That is two and a half full days—for a full-colour astro image. Taking a narrowband spectrum of the gases would mean a staggering amount of time if one was after the O-III line. Unfortunately, an accurate O-III spectrum is the main way one can determine the nebula's actual expansion velocity (planetary nebulae typically expand in the dozens of km/sec range). Acquiring a spectrum would take a large telescope of the size accessible only to professional astronomers. First, though, one must convince an astronomer that this object is so important it warrants big-telescope time—and cost. Good luck.

As co-discoverers, Drechsler and Strottner had the right to give it a name. They call it the Goblet of Fire Nebula.

HDW2 is a similar hard-to-understand striated planetary disc.

Was Thor's Helmet really snatched off his head by a Seagull?

Tiny Thor's Helmet looks more like a pathetic mouse in the talons of a hulking, skrawking Seagull Nebula in this 30 x 180-sec stack by Hirofumi Okura in Japan. Okura specialises in deep Hα and narrowband images of warm gas and dust-laden molecular clouds. His 2011 galactic cirrus shots of the southern polar region N-E of the LMC provided the first photographic demonstration of a 40°-long ultra-faint gas streamer that was later shown to be real and given the name *Magellan's Ghost*.

In this image Okura does it again: The faint filament of cool (~100 K) dust reaching from the Seagull's right wing down to grab Thor's Helmet and fly off with it.

Luckily for us, the real news in astronomy isn't quite so breathlessly extravagant as the above headline. However, there is real news here—the shock front exploding from the Wolf-Rayet star at the centre of Thor's Helmet appears to be inducing low-mass star formation—a rather unexpected phenomenon given that the ejected gas is only 20 to 30 solar masses itself, spread out over a large sphere. Here ASSA astro-imager Johan Moolman captures the very bright leading edges of shock fronts of gas being ejected by a super-hot ~35,000 K Wolf-Rayet star in the centre. The bright shock fronts mark the transition zone when gas compressed by a highly supersonic shock wave abruptly slows to subsonic speeds after the shock passes. In the image below we see red lines that mark the transsonic zone have a number of white dots that mark the positions of shock-compressed gas clouds dense enough to emit IR radiation—possible precursors to baby stars.

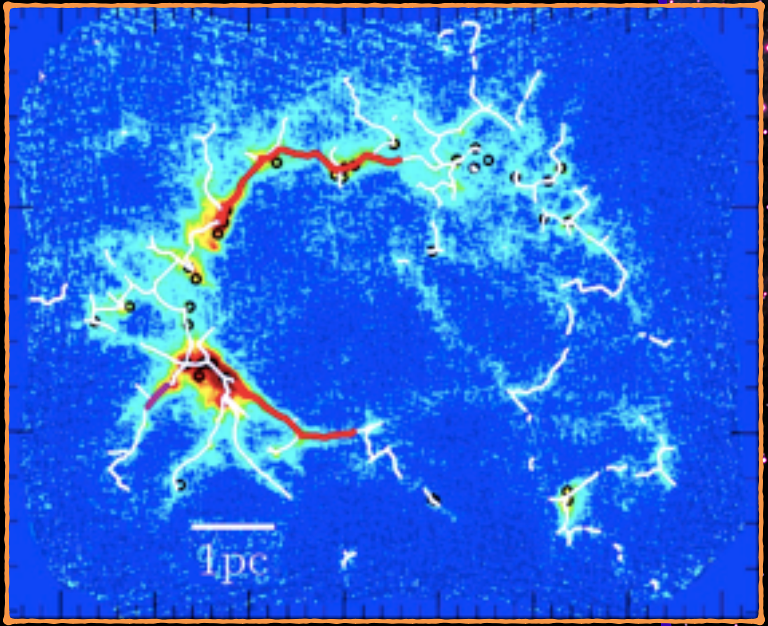


Image source: **Johan Moolman, ASSA**

Why is IC 2944/2948 called the Running Chicken Nebula?

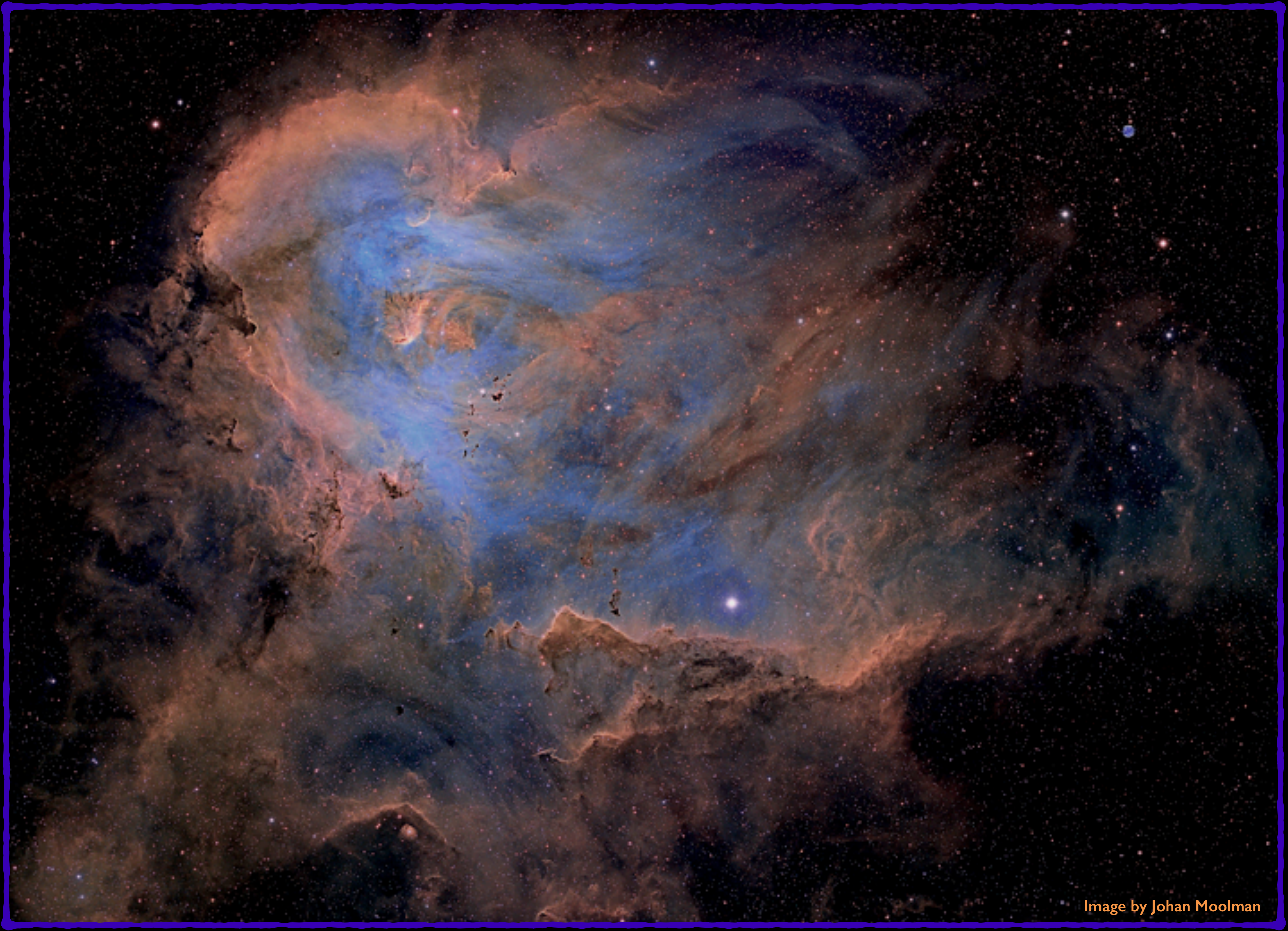
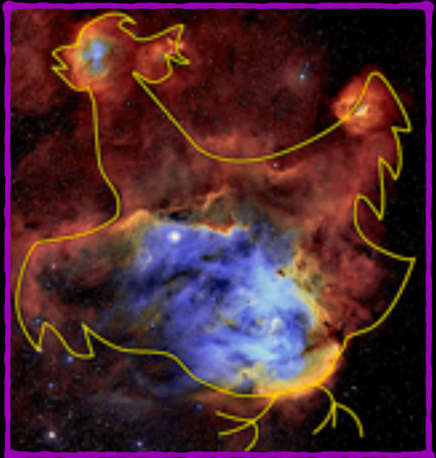


Image by Johan Moolman

The imaginatively named Running Chicken Nebula in Centaurus is a difficult object to image successfully. It lies in a region dominated by the bright 3rd magnitude star Lambda Centauri, whose glare easily wipes out subtle, dim nebulosity nearby. Most imaging attempts that do not evade Lambda Cen end up showing indistinct, tepid patches of red. Moreover, three nearby bright open clusters, NGC 3766, NGC 3355, and IC 2714 surround the region shown on the above page. Taken together, these usually translate into images of the Running Chicken Nebula more resembling the straw on the floor of the chicken hock (coop) than the chicken crossing the road.



So now you know how I got my name!

ASSA astro-imager Johan Moolman faced two problems as he tried to capture the above highly detailed and subtly nuanced image of one of the southern hemisphere's most elusive patches of nebulosity. First he had to solve the bright-competition problem by adroitly framing the imaging field in the recording chip of his ZWO 1600 camera at the focal plane of his Skywatcher Esprit 100ED APO Triplet in such a way that the nebulosity would just fill the imaging chip while excluding the bright stars nearby. The fact that there is no uniform bath of white glow dimming the delicacy of the nebula's traceries and colours testifies to the success of Johan's careful pointing and tracking.

Avoiding the glare was the lesser of Johan's obstacles. The larger problem was the bright suburban skies he lives under. These are light-polluted to a level of glare known as Bortle 6 in astronomy jargon. That means the Milky Way is just barely visible when it is overhead and only the brightest stars can be seen below 35° above the horizon. Worse, the bath of light from urban LED street and parking lot lights turns the sky an insipid hue resembling curdled cream. An image as finely detailed and subtle as Johan's would be impossible without adroitly selective filtration and carefully calculated exposure times.

Luckily for legions of aspiring astrophotographers like Johan, the hobby has become so profitable that astronomical equipment makers have invested huge sums to satisfy the demands of imagers. The telescope that produced the image above has a diameter of only 100 mm (four inches), yet the image Johan produced with it would have been the envy of a large professional observatory just 25 years ago.

Equipment investments have not gone into not just better and more finely resolving cameras, but also a wider choice of narrowband filters that imagers can choose to record light that reflects complex underlying physics we would not detect in broadband images. Nuclear, magnetic, and supersonic shocks produce spectral lines that reveal telltale signs of exactly what reactions are taking place inside and on the surfaces of stars, and in the thin gas and dust in between those stars and us. For this image Johan chose a hydrogen alpha (Hα) filter of 5 nm (nanometre = billionth of a metre) bandwidth, a doubly-ionised oxygen (or OIII) filter 3 nm wide; and a singly ionised sulphur (SII) filter of 3 nm bandwidth.

The reason for these choices is that Hα records the energy lost by a hydrogen atom as it cools from an earlier warm state as electrons drop from the third to the second valence or energy level. Hence an intense 656 nm red in an image is the telltale sign of large quantities of hydrogen in the nebula. OIII records the energy added to an oxygen atom when an electron collides with it in an environment warmer than about 10,000 K; the blue glow in this image comes from light emission at 500.7 and 495.9 nm. In the Running Chicken Nebula, the O-III emission is most likely coming from the hot star Lambda Centauri, which Johan carefully excluded from this image because its brightness would have overpowered everything else. The SII signal comes from warm sulphur, which indicates the presence of sulphur-based dust mixed in with the gas. Sulphur and silicon-based dusts are aliphatic (chain- instead of ring-like) which act as tracers of local magnetic fields generated by dust grains that are dipolar, with positively charged atoms at one end and negatively charged atoms or molecules at the other. SII is not as good as silicious dust at revealing magnetic activity, but is a very good tracer of kinetic temperature.

The red-edged clumpy features in the image are shock surfaces where high-energy electrons and protons penetrate into a dense gas/dust layer and raise its temperature till it glows above 3000 K. The delicate striations in the blue patches can reveal either magnetic field lines and/or the streamlines of high-velocity winds. The dense, dark blobs and specks are dense pockets of gas molecules and dust called Thackeray or Bok globules, some of which will collapse into infant stars.

What is the mystery hiding inside HH 34's enigma?

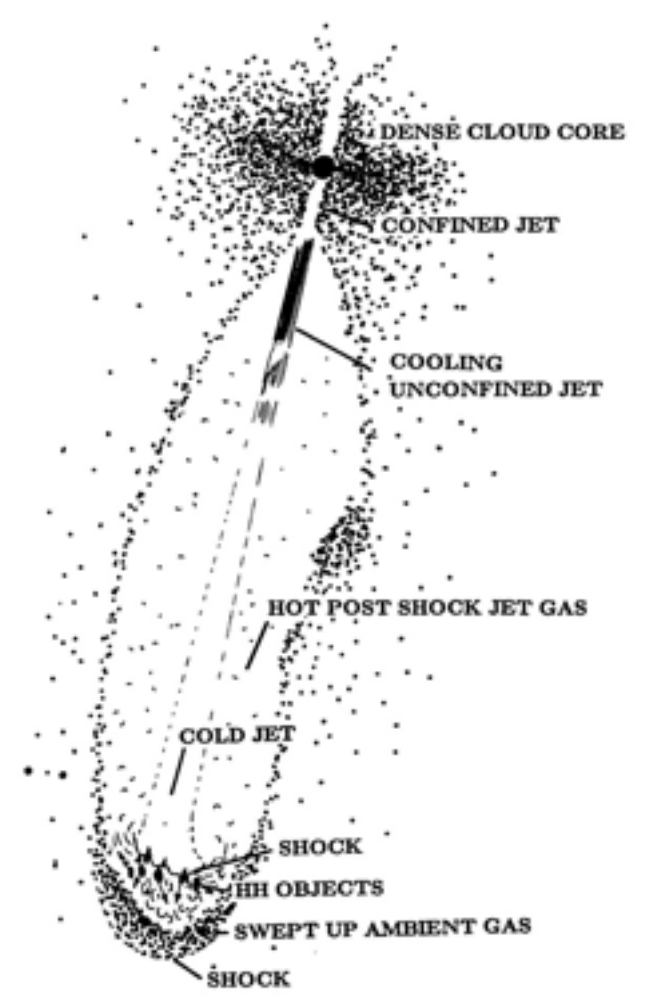
THIS PAINTERLY ABSTRACTION depicts a very young star in its first squall of life after being born. Its three principle components were captured in this spectacular image by the Hubble Space Telescope. The blue wisps in the lower left of the image have been daubed onto the sky by the long paintbrush of an infant star cocooned within the dusty dull red of a clump of molecular hydrogen gas to the upper right. The star has collapsed only quite recently into a dense ball massive enough to ignite fusion in its core. The surrounding cloud glows from within in several other places, revealing other protostars hiding deeply within their billowing birth cauls of dust.

The intense spike punching its way out of the cloud is an extremely hot collimated jet hurled from the young star by fierce magnetic fields powered by the star's rapid rotation. As this jet spits outward at Mach 3 or 4 through space, it collides with cold, dense gas hidden within the dark blob of a second cloud that is difficult to trace here. The cloud's cold gas quenched the jet so rapidly that it no longer emits in the visual light of this image. As if to spite its surroundings, the jet still hurls a massive amount of gas at supersonic speeds into the cloud in front of it. So rapid is the compression shock that the gas in front of the jet cannot move out of the way fast enough. It compresses into a dense lens-shaped shock front that heats into an incandescent complex of shock waves called a Herbig-Haro or HH object (after the two French astronomers who first explained them).

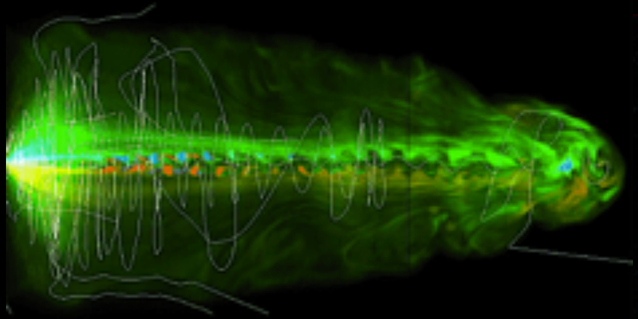
Although the jet extends the entire length between the infant star and HH34, only a fraction of it is visible in this image. The HH phase of a star's formation is relatively brief, only a few thousand years.

This image is an enlargement of a three-colour composite of the young object Herbig-Haro 34 (HH-34), now in the protostar stage of evolution. It is based on CCD frames obtained with the FORS2 instrument in imaging mode, on November 2 and 6, 1999. This object has a remarkable, very complicated appearance that includes two opposite jets that ram into the surrounding interstellar matter. This structure is produced by a machine-gun-like blast of "bullets" of dense gas ejected from the star at high velocities (approaching 250 km/sec). This seems to indicate that the star experiences episodic "outbursts" when large chunks of material fall onto it from a surrounding disc. HH-34 is located at a distance of approx. 1,500 light-years, near the famous Orion Nebula, one of the most productive star birth regions. *Source*: *ESO image eso9948c*.

The fiery art of losing a little to gain a lot

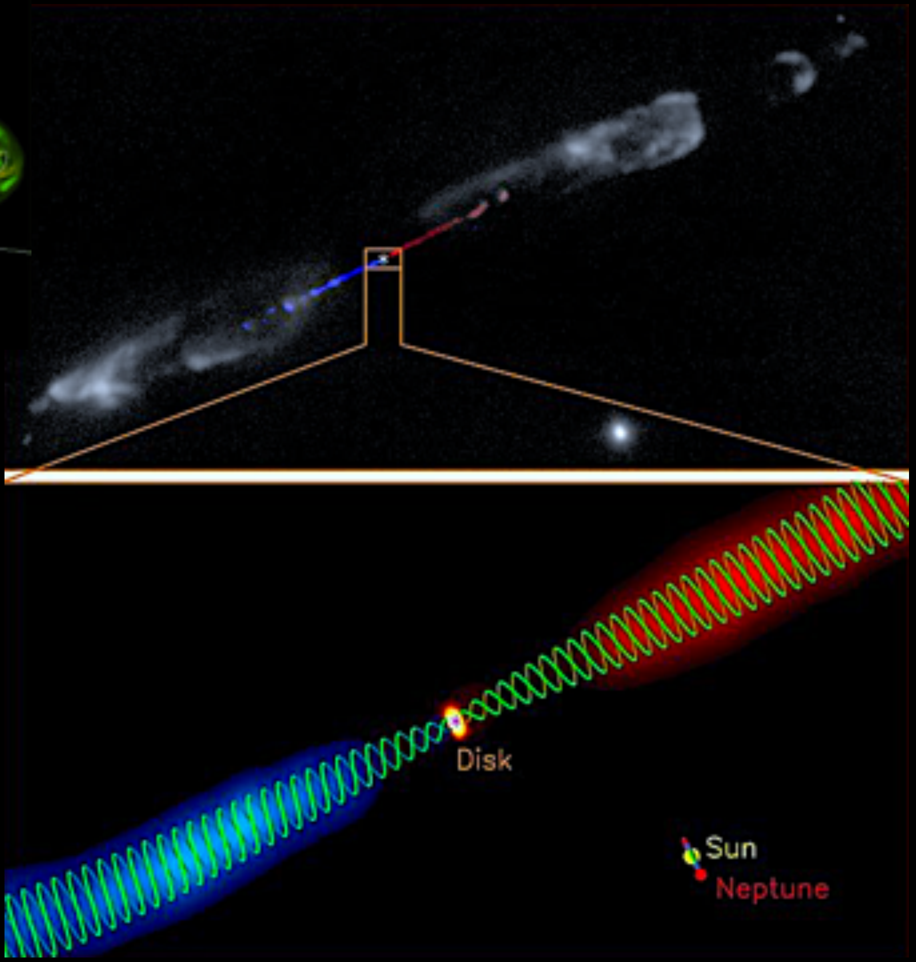


The supersonic outflow ejected from the magnetic north and south poles of an infant star produce a large oval-like cavity filled with hot ionised gas that shines brightly in visual and X-ray bands. Rapid cooling of a hot jet into a cold jet explains the inexplicably short spike jetting outward from the star. As the jet races outward it also cools, slows down (to 3.5 km/sec in this case), and no longer emits visual light. Cold or not, the jet's gases are still moving at a velocity high enough to compress a large, dense lens of matter which soon fragments into multiple shock fronts and dense clumps. Source: Reipurth et al, 1986, *Jet and energy source of HH34, Fig. 16*, A&A 164, 51-66.



When it comes to baby stars, any hopes for simple explanations are tossed out the window. Even the magnetic field that energise the protostellar jet model to the left is fiendishly complex—weeks of computer time go into a drawing like the one above. The thin lines represent magnetic field lines. Above, we see not one but four different sets of them, all emanating from one of the magnetic poles of the spinning star out of the field to the left. In the centre, a helicoid tube of field lines collimates the jet into a thin pencil as it speeds outward. Further outward, two other sets of field lines serve to confine the outward thrust into a gently flaring oval, and to mute the violence of turbulent shocks that result from such a forceful intrusion into the region's former tranquillity. The net result is clearly visible in the clumpy yet well constrained image to the right. It may look an unholy mess, but it is a very predictable one.

Ironically, protostellar jets serve to fatten up the underlying star. As angular momentum is removed via spin out the poles, it reduces gas pressure in the equatorial region of the star. The reduced gas pressure at the equator allows gas from the surrounding cloud to accrete onto the star's surface so rapidly that a tiny infant core grows into a massive hulking teen-ager within a few hundred thousand years. In star time, that is considered 'instantaneous'.



In 2018 an international research team led by Chin-Fei Lee in the Academia Sinica Institute of Astronomy and Astrophysics (ASIAA) made a breakthrough observation using the Atacama Large Millimeter/submillimeter Array (ALMA). Their study confirmed the presence of magnetic fields in a jet from a protostar. Such jets seem to play an important role in star formation. They help a protostar accrete mass from a disk of gas and dust by removing angular momentum from the disk and ejecting it out of the star's magnetic poles. The jets are highly supersonic (Mach 3 or 4) and collimated. Although jets have been long predicted to be powered and collimated by magnetic fields, no one was really sure about it. Now, thanks to the high-sensitivity of ALMA, Chin-Fei Lee and his colleagues finally confirmed the presence of magnetic fields in a protostellar jet by detecting molecular line polarization. The magnetic field in the jet is likely a helicoid stream. If so, the physics of the protostellar ejection process may be more than merely visual analogs to the vastly larger and more powerful jets that erupt from active galactic nuclei (AGN) that are typically energised by a supermassive black hole in the centre of a galaxy. If calculations and computer modelling demonstrate the two phenomenon are indeed related, it would be yet another example of how relatively simple physical laws determine the properties of a large range of sky objects that we study. *Watch the video here*. Source: Lee et al. *Unveiling a magnetized jet from a low-mass protostar*, *Nature Communications* (2018).

Why are the Fornax A galaxy's radio lobes so huge?

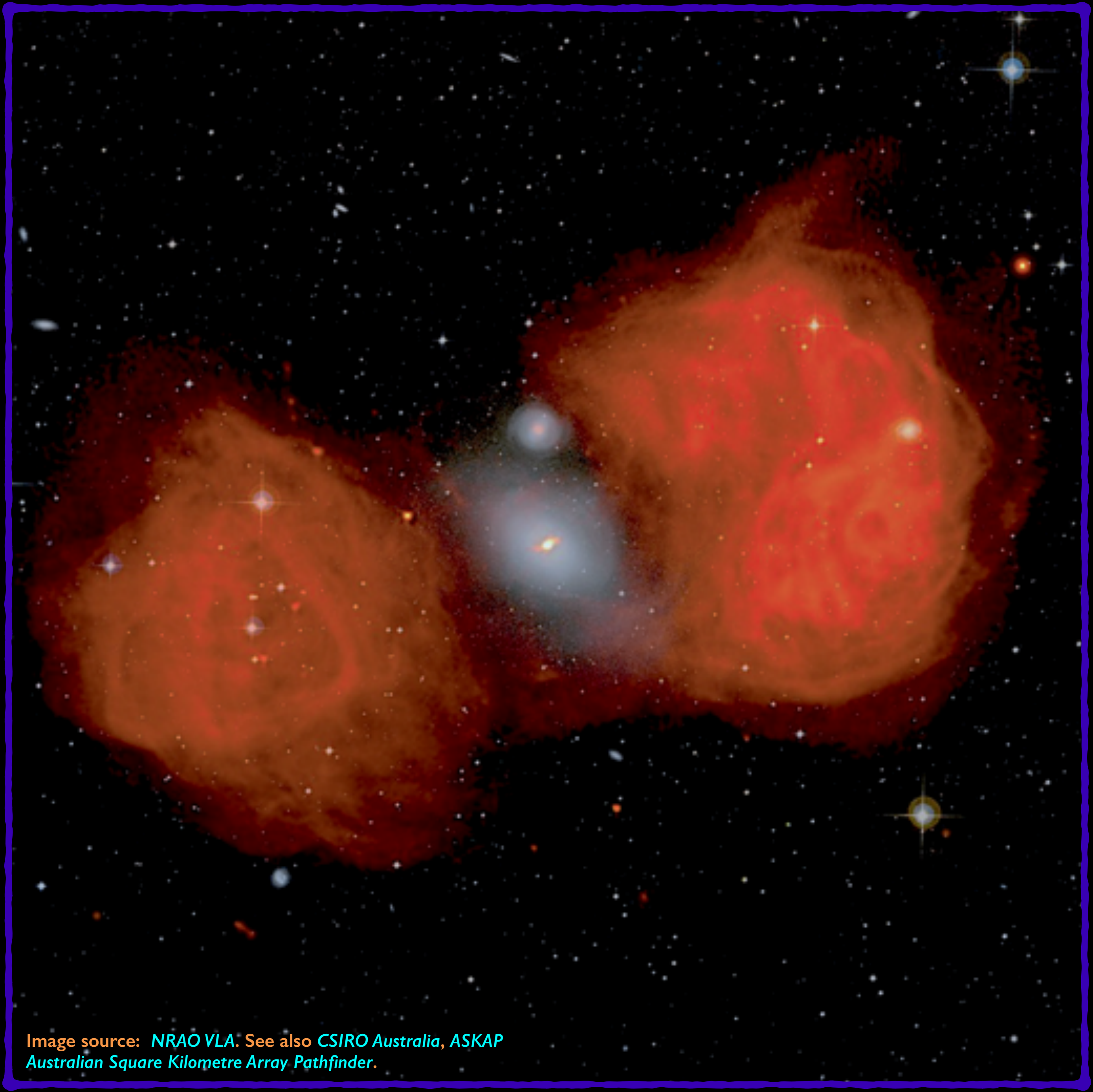


Image source: *NRAO VLA*. **See also** *CSIRO Australia*, *ASKAP Australian Square Kilometre Array Pathfinder*.

GIGANTIC RADIO LOBES emanate from NGC 1316 in the Fornax galaxy cluster. The two ball-shaped emission lobes radiating infrared light are twice the size of the galaxy itself. Why are they so gigantic?

Fornax A is a galaxy with an accreting-disc black hole in its core. The black hole is spraying near-relativistic jets out of its poles. The poles themselves can be seen as tiny ansae extending a few mm beyond the core of the galaxy (bright dot) at an angle of ~70°–250° and bisecting the red radio lobes. The jets heat the thin gas in the surrounding intergalactic medium to kinetic temperatures above 100 million degrees K. The enormous volumes of space in between galaxies in a cluster is one of the hottest yet most rarefied environments in the Universe. On average there is only one atom per cubic meter in this medium ($<10^{-27}$ kg/m^3), but they have so much stored kinetic energy that their kinetic temperature is equivalent to 10 million degrees K.

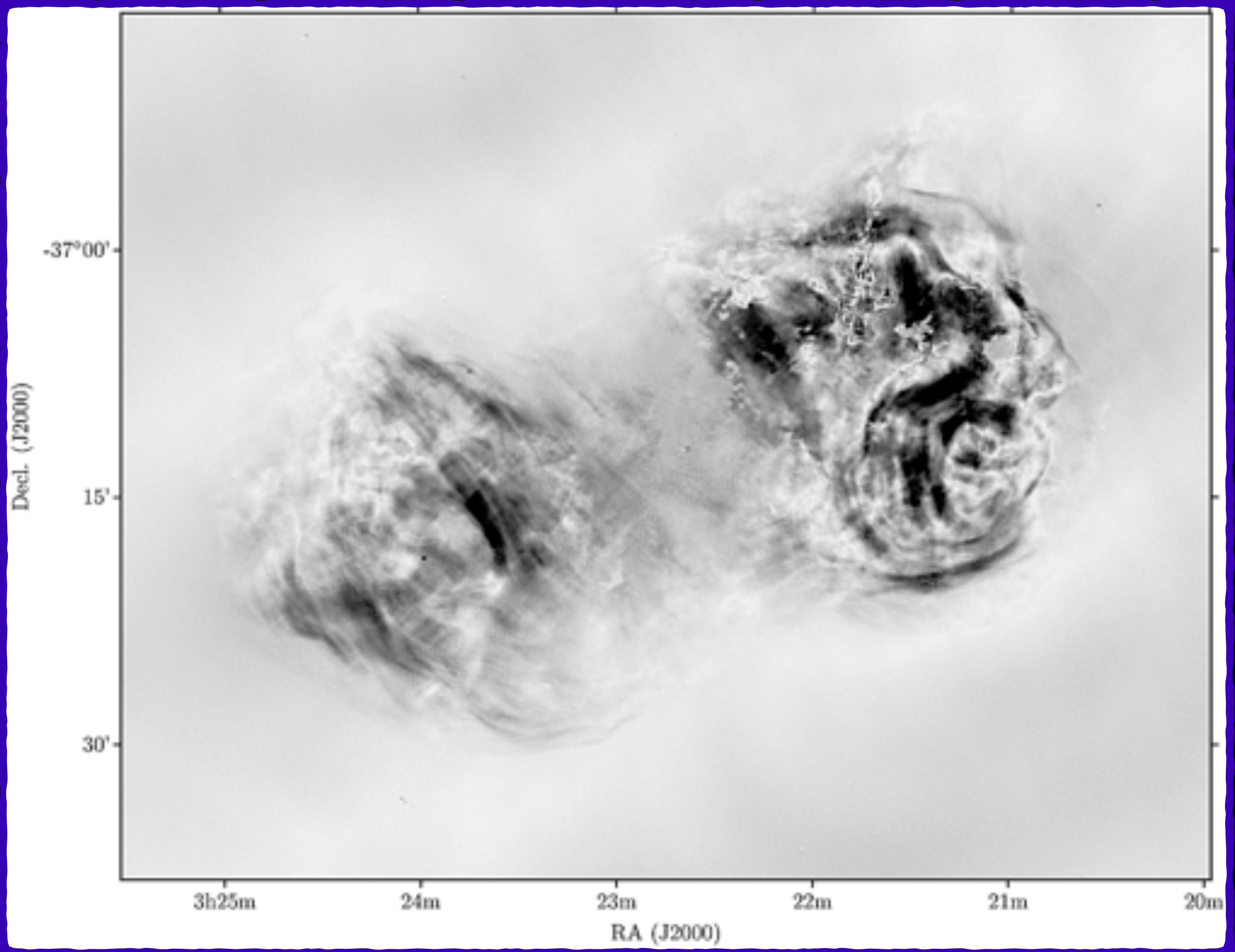
Temperature in space is not what your skin feels, it is the accumulated kinetic energy in a particle after billions of years of being bombarded by cosmic ray collisions, thermal and supersonic shock waves from supernovae, extremely hot O stars, and infalling galaxies ejecting relativistic particles from their poles. (Note that not all black holes are active; if there is no nearby gas to accrete, they are quiescent and undetectable.).

Here, the white glow in the center is the visible galaxy NGC 1316 that any amateur astronomer with an 8-inch telescope can see as a faint white fuzzy. But where is NGC 1316 getting all that gas?

Notice the small spiral galaxy above it? It is NGC 1317 and these two galaxies are merging. Gas and dust are being pulled out of the small galaxy into the center of NGC 1316. The black hole nestled in NGC 1316 spins the accreted gas into a razor-thin disc rotating around its equator at hypersonic velocities. The huge radio lobes to either side of this merger are the telltale signs that a black hole is being fed more than it can digest. The magnetic field lines generated by all those electrons rotating around the accretion disc spiral up the sides of the spherical black hole, and twist into a helically rotating jet that speeds straight as an arrow out of the polar axis into intergalactic space. Large numbers of electrons and protons are swept along with the magnetic field lines. When these particles expand and cool, they interact with the hydrogen and other atoms that populate intergalactic space. These atoms may be few in number, but over the vast distances involved here (roughly 1.5 million light years) that is a lot of magnetic field/particle energy transfer from the jet to the intergalactic medium (IGM).

The end result is a huge reservoir of hot gas that emits radio waves, observed as the orange (false-color) blobs in the above image. The radio image is superposed on an optical survey image of the same part of the sky.

Strange patterns in the radio lobes (see right) suggest that slight changes in the directions of the jets acquire patterns of their own due to the differences in gas density and magnetic field strength of the huge volume of space surrounding a galaxy.



The fine structure of the energy transfer from jet to IGM is shown in the image above. These are the billowing ends of powerful jets shooting spun-up, escaped material far into space. The core of NGC 1316 is the tiny dot in between the two giant radio lobes. In this image, darker areas represent regions of strong linearly-polarised emission. The eastern (left-hand) lobe shows multiple layers of parallel filaments of polarised radio emission as dark streaks whose cause is thus far unexplained. Similar laminar patters are observed in other galactic radio lobes as well, and these too are inexplicable given current data.

The right-hand lobe presents fewer conundrums. The round multilayered region near the bottom of the lobe is actually a magnetic shadow cast by a spiral galaxy in front of the lobe that is so dim in visual light that we detect it only by its shadows as revealed by the NGC 1316 radio lobe.

Taken together, all these phenomenon boil down to the fact that the seemingly frail, thin medium we call intergalactic space is an extraordinarily elusive complex of mass and energy with many secrets still to be observed and explained.

For a more complete analysis of the structures in the above image, see '*Searching for magnetic fields in radio galaxy Fornax A (NGC 1316)*' from the CSIRO Australia Telescope National Facility.

Why is M33 in Triangulum such a rhapsody in blue?

THERE IS MORE TO M33 THAN WE SEE IN THE EYEPIECE

The Triangulum Galaxy M33 is the 3rd largest galaxy in the Local Group of galaxies, after the most massive galaxy, Andromeda (M31) and the Milky Way in second place as slightly less massive. M33 is over thirty thousand light-years across, and more than two million light-years away. M33's hazy blue outer disc shown here likely originated from a tidal disruption by M31 one to three billion years ago. Two flat discs like spiral galaxies can interact in so many ways involving different angles, squash planes, and relative velocities that it is very difficult to analyse what happened billions of years ago. Today we know mainly that prodigious amounts of gas torn away from both galaxies now appears to be returning to M33's disk as fresh star formation fuel.

The gravitational dynamics of rotating disc galaxies tends to direct infalling gas into the disc from the disc plane rather than tumbling in from all sides. As the gas enters the outer disc it heats up, providing fresh star fuel that will feed M33's present high rate of star formation for one to three billion years. The blue colour was chosen to indicate that the gas is relatively cool compared with the much warmer gas in the disc itself.

Despite its gravitational reprieve, M33 will eventually exhaust its star formation fuel, only to find itself being sucked into a truly whopping merger four to six billion years from now, when all three galaxies will collide in a spectacular fury of wrenching push and shove. Another few billion years will then pass before all the gravitational imbalances have settled their differences in the form of a 'red and dead' giant elliptical galaxy. One of many truths we find in astrophysics is that gravity, the feeblest force in the galactic universe, is also very patient.

Is NGC 474 a galaxy or an onion?

Elliptical galaxies are generally known for their smooth surface density profiles—especially when compared with spiral galaxies. One particular class of spirals are called flocculent spirals because of their multiple dust lanes and fragmentary spiral arms. NGC 470 on the left is such a galaxy. But this image shows structures around the elliptical galaxy NGC 474 on the right that look somewhat like the flocculent shell version of the beclotted spiral arms next door. Why has NGC 474 such a layered look instead of the traditional elliptical galaxy's smooth, featureless ball?

These features are due to smaller dwarf galaxies that were pulled into the once-smooth NGC 474 ellipsoid within the last billion years. The pre-infall ellipsoid had long ago been smoothed by the interaction of multiple spiral and irregular galaxy collisions far back in the early history of the universe. Galaxies were much smaller and more inchoate in the first three billion years of the universe, hence they interacted much more often. One result was prodigious star formation. Many galaxies simply ran out of star-making gas. They also tended to gather into galaxy clusters, which further reduced their ability to make stars. Stars go from blue to red as they age. Hence galaxy clusters today are mostly 'red and dead'.

Despite how close NGC 470 may seem in this image, the two galaxies have never interacted—if they had, NGC 470 would have been ripped to shreds and smeared all over this image like NGC 474's other low-mass victims. Image courtesy of the Dark Energy Survey.

Why does NGC 5291 have the worst table manners in the sky?

GALAXIES HAVE NEVER BEEN KNOWN AS DAINTY DINERS. This image from the SMARTS 0.9-meter Telescope at Cerro Tololo Inter-American Observatory shows the result of a truly spectacular galactic food fight. The bloated galaxy NGC 5291 (the oval cloud in the centre with its dusty belt sagging well below its belly) took rather too licentious a lurch toward a tasty morsel of spiral galaxy some 300 million years ago and left behind this unedifying mess of blue luminous X-ray bones splattered left and right. The clumps glow strongly in GALEX X-ray images but show no cooling hydrogen (H-alpha) signature, which suggests gas starvation after a blistering starbake heated the poor spiral's gas to over 100 million K. Let's not contemplate what the napkin must look like, OK? Astrophysicists know of some messy after-dinner behaviour it would rather the public not ask about. (Which might explain the arcane language they devise to explain it to each other.)

Yet even then NGC 5291's appetite was not sated. The galaxy is now sipping on a piña colada in the shape of PGC 48894, which looks more like a comma than its rather more prosaic moniker, the Seashell Galaxy. The uninvolved onlooker to the upper right is the spiral galaxy PGC 48877, and the complex barred galaxy below left is PGC 48911 (which may have similar designs on the dwarf galaxy PGC 718090 just below it).

Further information here: *1*, 2.

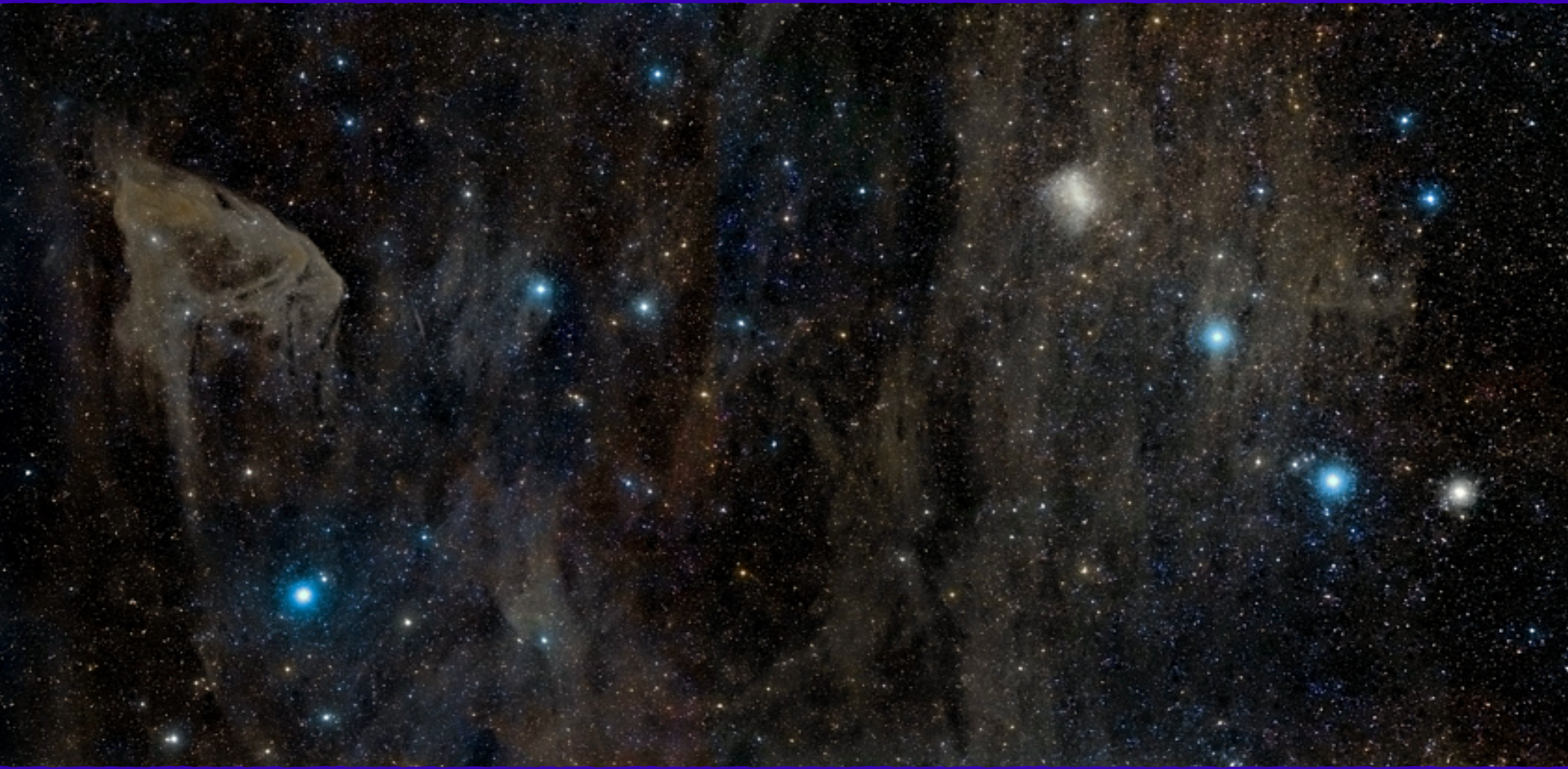
Source: The SMARTS 0.9-meter Telescope, constructed in 1965 by Boller & Chivens. *Membership in the four-telescope SMARTS open-access telescope network is open to individuals or institutions.* For more science & instrumentation information, *see this page*. Download the *Operating Manual here*.

How does a gas cloud like Monoceros R2 get so streaky?

Source: Wide-field Mosaic II camera on the Blanco 4-meter telescope at Cerro Tololo Interamerican Observatory, Chile.

THIS PAINTERLY INFRARED IMAGE penetrates opaque curtains of dust that becloud the messy origins of hot, young star clusters In this Blanco 4-Meter Telescope image, two infant clusters' first stars have burst into life in the centre and bottom centre. If we lived next door to these clusters—say about half the distance between the Sun and Alpha Centauri—we would see an intricately cloud-wreathed sky speckled with stars like the computer simulation creator Teun Van Der Zalm's works *Interstellar Clouds* and *Stellar Nurseries*. The intricate folds, loops, filaments, and bright clouds are fairly standard scenery in the theatrical playbook of molecular clouds collapsing into young clusters. The chaotic palette seen here portrays starry sculpture in the making—imagine Michelangelo chipping away at a large chunk of marble to reveal the beautiful young man named David hidden inside all along just waiting for the right man with the right chisel. The streaming lacework in red to the left and right reveal large-scale magnetic fields aligning immense numbers of tiny silica-based dust specks into dipolar streams that have arrived at the party too late to join in the star-making. The two intensely white glows are hot young stars in the first one to three hundred thousand years of their long lifetimes ahead. Because the interstellar dust is opaque to visible light, infrared and radio observations are crucial in our understanding of the earliest stages of the stellar evolution—and unveiling this majestic scene for us to enjoy.

Why does Galactic cirrus look so different from cirrus above Earth?



The presence of Barnard's Galaxy NGC 6822 overexposed as the bright patch in the upper right centre of this image gives us a convenient yardstick to gauge the height of the Galactic cirrus that shrouds our night skies without us being aware of it. 'Galactic cirrus' is a convenient rubric for clumpy and filamentary patches of microscopic dust that lie within thin structures only a hundred parsecs (326 light years) above and below the part of the disc in which the Solar System resides. Barnard's Galactic declination is –18.4°, so simple trigonometry places these clouds in the middle regions of the thin disc.

NGC 6822 Barnard's Galaxy in Sagittarius/Capricornus is the bright patch upper right centre. The filamentary streaks in front of it are made of Galactic disc dust whose only illumination is the combined light from the Milky Way itself. These dust clouds are only a few to a few dozen particles per cubic meter, hence their faint visual presence at 25 to 28 magnitudes per arcsec^{-2}. Image © 2021 *originally published in IceInSpace 19 Aug 2021*.

Where does a queenly raiment like NGC 3628 keep its Crown Jewels?

NGC 3628 IS A LARGE, EDGE-ON SPIRAL GALAXY and one of three galaxies in the "Leo Triplet" so popular with visual and imaging astronomers alike.

This galaxy, NGC 3628, is best known for its warped disc and the long tidal tail seen in the images in the montage on the following pages. For professional astronomers, the intriguing feature of NGC 3628's disc is the extraordinarily thick and bulbous outer disc which extends much higher above and below the galaxy's plane than most spiral galaxy gas discs. Galaxy collisions usually strip away disc gas, but NGC 3628's 260,000 light year tidal tail seems not to have affected the disc gas at all.

The clumpy tail results from gravitational interaction with the nearby M66 member of the Leo Triplet (above this scene on the right side of NGC 3628).

Yet until five years ago, there was a celestial secret hiding within the profuse detail of this scene—a sphere of stars as dense and populous as Omega Centauri in the Milky Way. Look carefully—can you spot it in this image? It's in there.

Don't feel bad if you don't pick it out it right away. Astronomers didn't notice it until 2015.

Source:
This image was acquired with the B (blue), V (green), I (orange) and Hydrogen-Alpha (red) filters using the Mayall 4-meter telescope at Kitt Peak National Observatory by T. A. Rector of the University of Alaska Anchorage and H. Schweiker of the NOIRLab.

Watch this *AURIGA Project simulation of stellar motions in a short-barred spiral galaxy* (as NGC 3628 is suspected to be, based on a red DECaLS DR3 image shown below. in which the bar is seen directly along our line of sight).

Why is the collisional stream of NGC 3628 flying the wrong way?

THIS WAY TO M65

Unrelated remote galaxy hiding behind known NGC 3628 dwarf.

THIS WAY TO M66

CROWN JEWEL UNVEILED: *NGC3628-UCD1* ultra-compact dwarf galaxy core similar in mass to NGC 5139 Omega Centauri.

In astrophysical terminology, tidal streams like the one above that was stripped from the Leo Triplet galaxy NGC 3628 are considered diagnostics of galaxy formation. The serenely mature spiral galaxies we gaze upon today often had messy childhoods and adolescence. (See *1*, *2*, *3*.) In the burgeoning community of Pro-Am collaborations, professional astronomers more accustomed to recording data with 8-metre telescopes are also gratified with the results they see from small telescopes like the super-wide super-sharp Takahashi FSQ106 series (4 inch) and RCOS or Planewave 17 and 18.5 inch instruments. Pro-Am collaborations produce results that enable theoreticians to better constrain the conditions that shape galaxies.

This detailed image was captured by Mark Hanson at his Stellar Winds Observatory near Animas, New Mexico, USA. Mark contributed to the 2016 *Dwarf Galaxy Survey with Amateur Telescopes* (DGSAT) study in which RCOS, PlaneWave, and Takahashi-class telescopes from 106mm up to 0.8 m (30 inches) were configured to discover ultra-faint (27.5 mags per sq arcsecond) stellar streams of dwarf galaxies accreted into the halos of larger galaxies. The telescope Mark used in the DGSAT project was a 24-inch Planewave R-C. The above and next two NGC 3628 images came from Mark and his colleagues. Read a *profile of Mark and his imaging methods here.*


©Mark Hanson "Stellar Winds Observatory" a/k/a Stan Watson Observatory

NGC 3628 IS WHIMSICALLY KNOWN AS THE HAMBURGER GALAXY. It is a barred spiral galaxy about 35 million light-years away in the constellation Leo. It was discovered by William Herschel in 1784. Today the galaxy is known as part of the Leo Triplet. This trio is a perennial favourite among amateur astro-imagers. The Leo Triplet's formal identities are NGC 3623 (M65), NGC 3627 (M66), and NGC 3628 (the 'Hamburger Galaxy' because it looks like one in a telescope).

NGC 3628 has been the subject of much attention since Fritz Zwicky reported an 'optical plume' extending from NGC 3628 in a clumpy shallow arc extending 80 kpc (260,000 ly). Zwicky calculated that it had a total H_1 mass of 540 million solar masses (M_{sol}), or about 15% of the total H_1 mass in the main body of NGC 3628 itself. Moreover, the galaxy's gas and its stars rotate in opposite directions to each other—a signature of galactic slide-by interaction as distinct from pass-through interaction. Slide-by interactions pull off tidal streamers while pass-through interactions produce starbursts of young clusters. Photometric and spectroscopic studies reveal that the NGC 3628 plume underwent a remarkable epoch of star-forming activity about 540 million years ago.

The clumpy nature of the NGC 3628 plume is clearly seen in the images on the next two pages. The first image is partly inverted to show faint structures, and partly in traditional view to make it easier to identify stellar structures. This presentation style was developed by David Delgado-Martinez in collaboration with several amateur astro imagers with a long-standing interest in discovering ultra-faint accretion structures around galaxies.

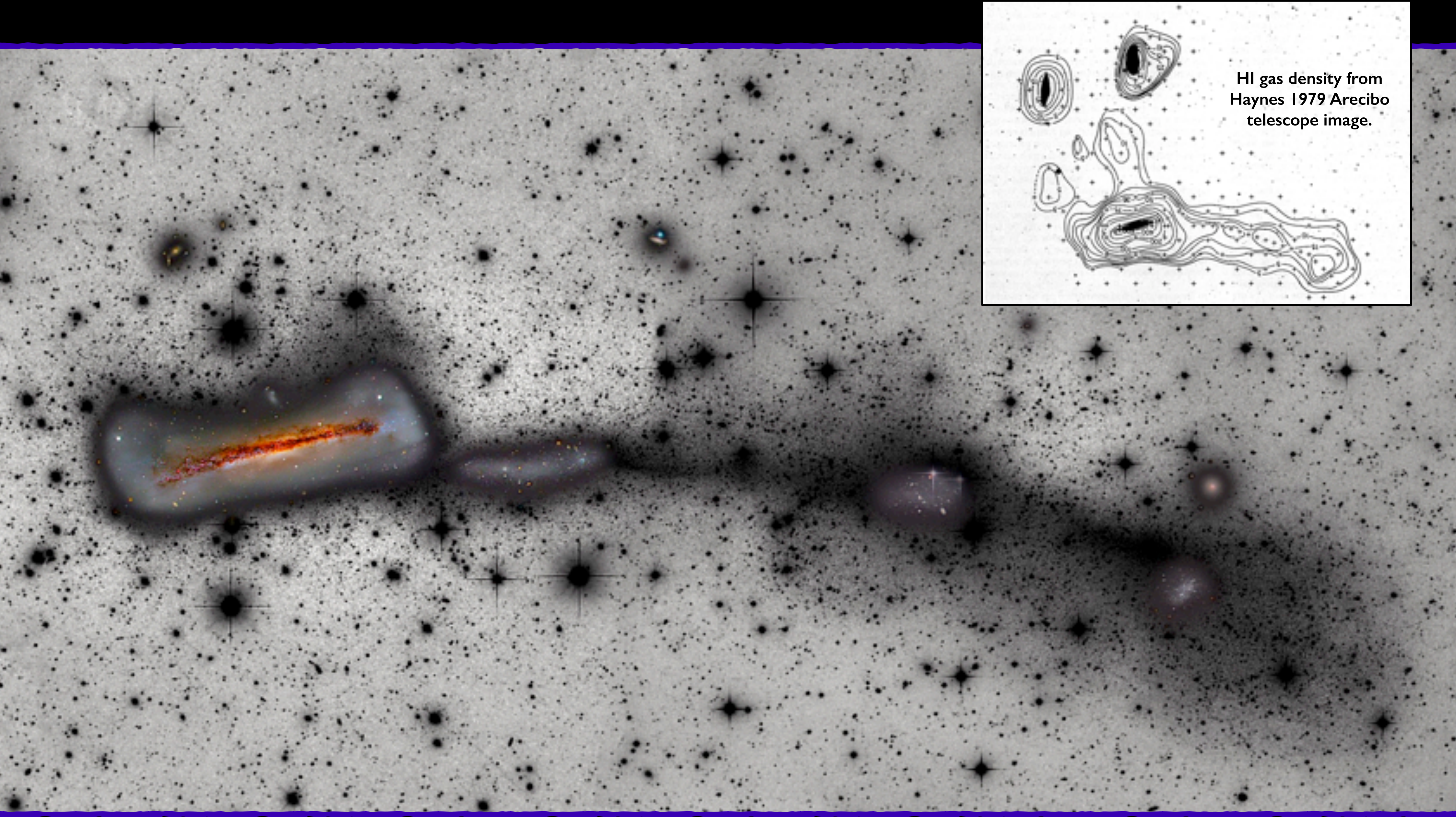
There are two major mysteries about NGC 3628 and the Leo Triplet in general. The first is how the apparent core of an accreted galaxy (NGC3628-UCD1 pointed out above) found its way to the largest clump next to the main galaxy—this object was, after all, discovered only in 2016. If this is indeed the core of a dwarf galaxy, where are the rest of the dwarf's stars? There is no firm evidence of faint stellar streams wrapping around NGC 3628. All we can do based on current observations is to surmise the disrupted dwarf's stars are mixed in with NGC 3628's disc stars. They also might be a significant component in the galaxy's counter-rotating star versus gas discs.

The second problem with NGC 3628 is its Inertial Enigma—why its 80 kpc 'plume' lies along a curve whose shape and mass distribution cannot be plausibly visualised as resulting from an interaction with NGC 3627 (M66)? The only kinematic orbital projection based on computer calculations was made by *Arnold Rots way back in 1978*—an era when astronomical projections of stellar motions were very coarse-grained by the standards of N-body and moving-mesh calculations today.

In 1998 *Frederick Chromey et al* updated the three-body orbital models for the tidal interactions between NGC 3628 and its companion NGC 3627, which reproduce the formation of a long plume and give a lookback time of 800 million years since their closest approach or perigalacticon at 27 kpc (88,000 ly). Gas removal by ram pressure and stellar redistribution by tidal effects are two distinct processes, neither of which seem to suggest plausible orbital pathway that reproduces the distribution we see in the Leo Triplet today.

Section 2 of a *1993 paper by Xiaolei Zhang et al* parses out the complexities or galaxy rotation and interaction direction. In it, Fig. 2 reproduces the 1978 Rots kinematics more clearly than the original 1978 paper. Still, the enigma remains

Source file: *Stellar Winds Observatory at DSNM, Animas, New Mexico*



HI gas density from Haynes 1979 Arecibo telescope image.

MARK HANSON'S ULTRA-FAINT DUST IMAGING

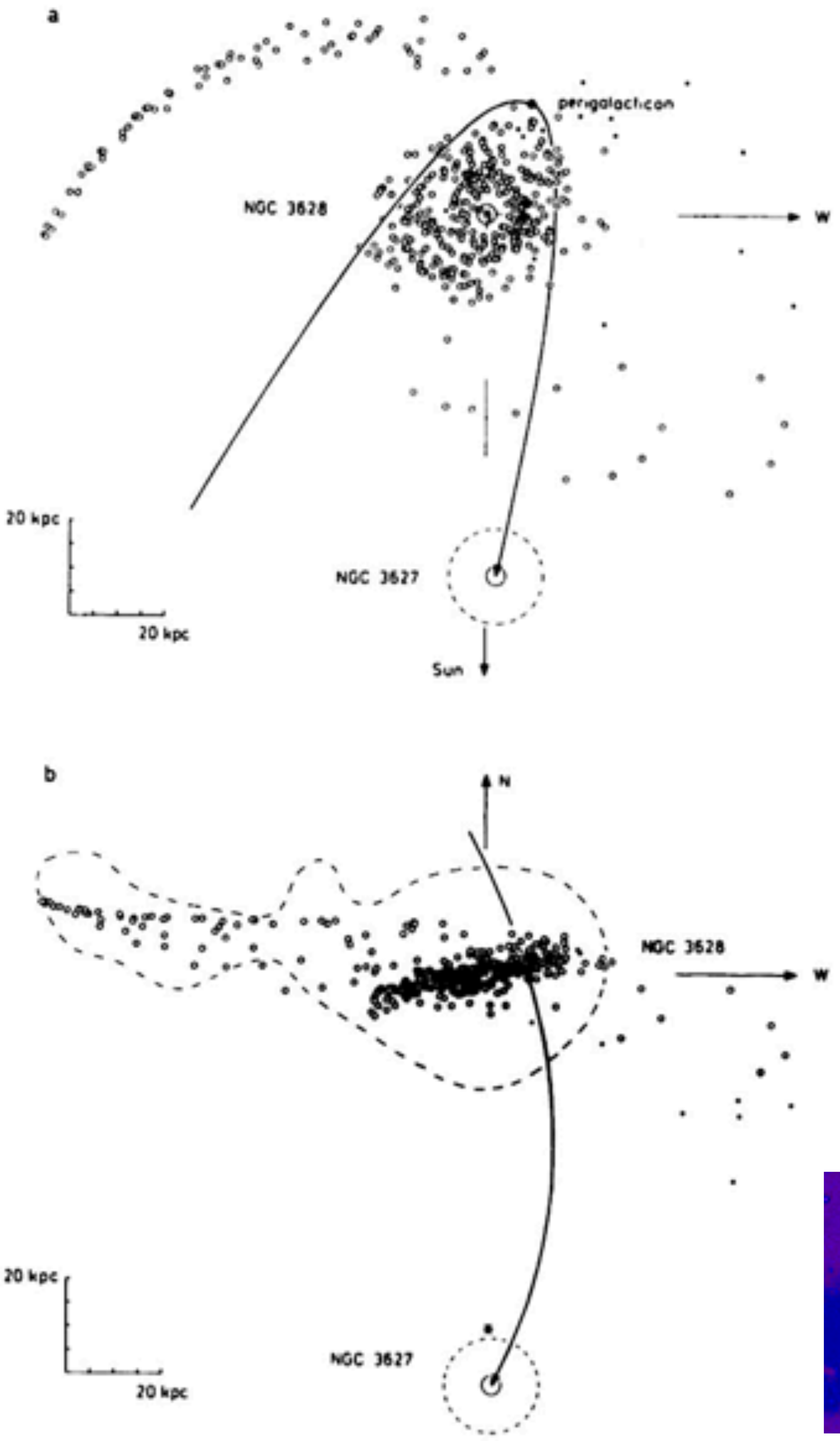
Mark Hanson has been an amateur astro-imager for over 25 years. He started out with a local group in Wisconsin, but realised that he needed to move to darker skies. He moved his equipment to Animas, New Mexico in the USA, where he could operate his equipment remotely. Mark is a member of the team of Pro-Am astronomers who search for galaxy merger remnants led by Dr. David Martínez-Delgado of the *Max-Planck Institute* for astronomy and *R. Jay GaBany* who oversaw Mark's images that have been reproduced here.

The David Martinez-Delgado & Jay GaBany 2008–2010 collaboration *Stellar Tidal Streams in Spiral Galaxies of the Local Volume: A Pilot Survey with Modest Aperture Telescopes* was conducted with three privately-owned observatories in Europe, USA, and Australia.

The members of the faint-stream imaging group acquire images reaching magnitude 27.5 to reveal ultra-diffuse and faint stellar tidal streams. The debris streams originate in tiny dwarf galaxies that have been accreted and absorbed into larger galaxies over the last several billion years.

Due to the complex and often competing interactions of mixed star/dust/gas particle masses and the forces of turbulent shock waves, magnetic fields, and gravity, the tiny dwarfs are never completely absorbed but rather leave behind thin streamers of stars whose uniform chemical mix and age can be used to trace to their original parent galaxy. The *Milky Way presently has 23 tidal streams*, some of which have been tracked down via a mere two hundred stars.

Mark Hanson acquired the data that went into these images using three telescope/imaging systems spread over five years of patient data collection. *See his website here*.



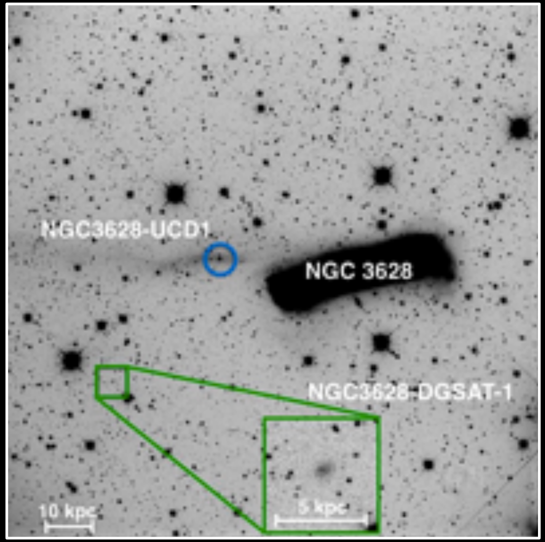
LEFT: The 1978 Arnold Rots 3-body interaction calculations for the orbital encounter between NGC 3628 and NGC 3627 (M66). Image (a) looks downward through the polar axis of NGC 3628. M66 moves inward from the left and above NGC 3628 in a parabolic arc that loops to the perigalacticon point 27 kpc from NGC 3628's polar axis at the disc plane, then sweeps beneath the galaxy to reach its present position. Perigalacticon occurred an estimated 800 million years ago, hence the total time span shown in the parabola in image (a) would be perhaps 1.6 billion years. That is a great deal of time for tidal gravitation to pull stars and gas from the parent galaxies into a long chubby filament better described as a plume. Many of the NGC 3628 plume's features today can be explained by the approx. two hundred million years the galaxies were close enough to each other for tidal stripping to take place. Imagine for a moment that you are standing by the side of a road just as a large truck passes. As it recedes into the distance, gusts of debris follow that riffle your hair and blow dust in your eyes. You have just experienced what NGC 3628 once experienced in v—e—r—y slow motion.

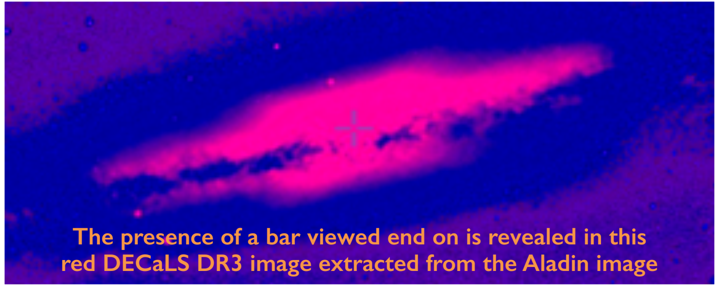
Image (b) shows the encounter as seen from NGC 3628's disc plane. M66 does not actually punch through NGC 3628; it was 27 kpc behind NGC 3628 when it crossed the disc plane. The mass exchange in this encounter was almost wholly tidal, since only the far outer discs of either galaxy would have experienced ram pressure stripping. The slow velocity of the encounter's prograde motion with respect to NGC 3628's rotation resulted in over 1 billion solar masses of HI gas being gravitationally extracted from NGC 3628 into the plume feature we see above. Much less gas was lost from M66 because the direction of the passage was retrograde with respect to its disc rotation. The route of the passage was in effect bucking a headwind. Even so, at least two large clumps of HI were removed from M66 and still reside near it today.

PREVIOUS PAGE: The four clumps identified on the previous image reveal that much of the HI gas that was removed from the galaxy was then turbulence-shocked into forming three well developed OB associations highlighted in the image above. Clump 2 probably did not have the critical mass necessary for H_I clouds to collapse into H_2 molecular hydrogen clouds that contain large quantities of gas in the centre surrounded by a large sphere of hydrogen and dust debris swept up in the gas stripping maelstrom. The light profile of the plume is approximately constant, 26.5 mag arcsec^{-2}, which is the same surface brightness as the optical edges of the disk. These observations support the theory that the tidal plume was formed from material in the outer disc of NGC 3628. If we look back on the page titled 'Rhapsody in Blue' some 10 pages earlier, and consider the enormous mass of H_I gas that exists in M33's outer disc that can be traced only by 21cm radio and CO emission studies, and add the fact that NGC 3628 may have undergone nearly a complete prograde revolution during the time it was being tidally stripped by M66, we can more easily understand why the plume had so much gas to make its stars with.

The H_I gas density is nearly constant along the plume and about the same gas density as in the outer envelope of NGC 3628—consistent with the gas dynamics of tidal stripping. The three star-specked optical clumps in the plume are coincident with H_I density peaks. The stellar population's average age of several hundred million years in the three clumps is consistent with star formation ensuing after the time of perigalacticon. The stellar masses of a few times 10 million solar masses are typical of massive star-forming complexes elsewhere in the universe. The proportion of stellar mass versus HI mass suggests a star formation efficiency in the plume of about 4% overall.

RIGHT: 2015 discovery image of ultra-compact dwarf galaxy NGC3628–UCD1 in DGSAT paper #1, 'Discovery of low surface brightness systems around nearby spiral galaxies', *Javanmardi et al 2016*.




The presence of a bar viewed end on is revealed in this red DECaLS DR3 image extracted from the Aladin image

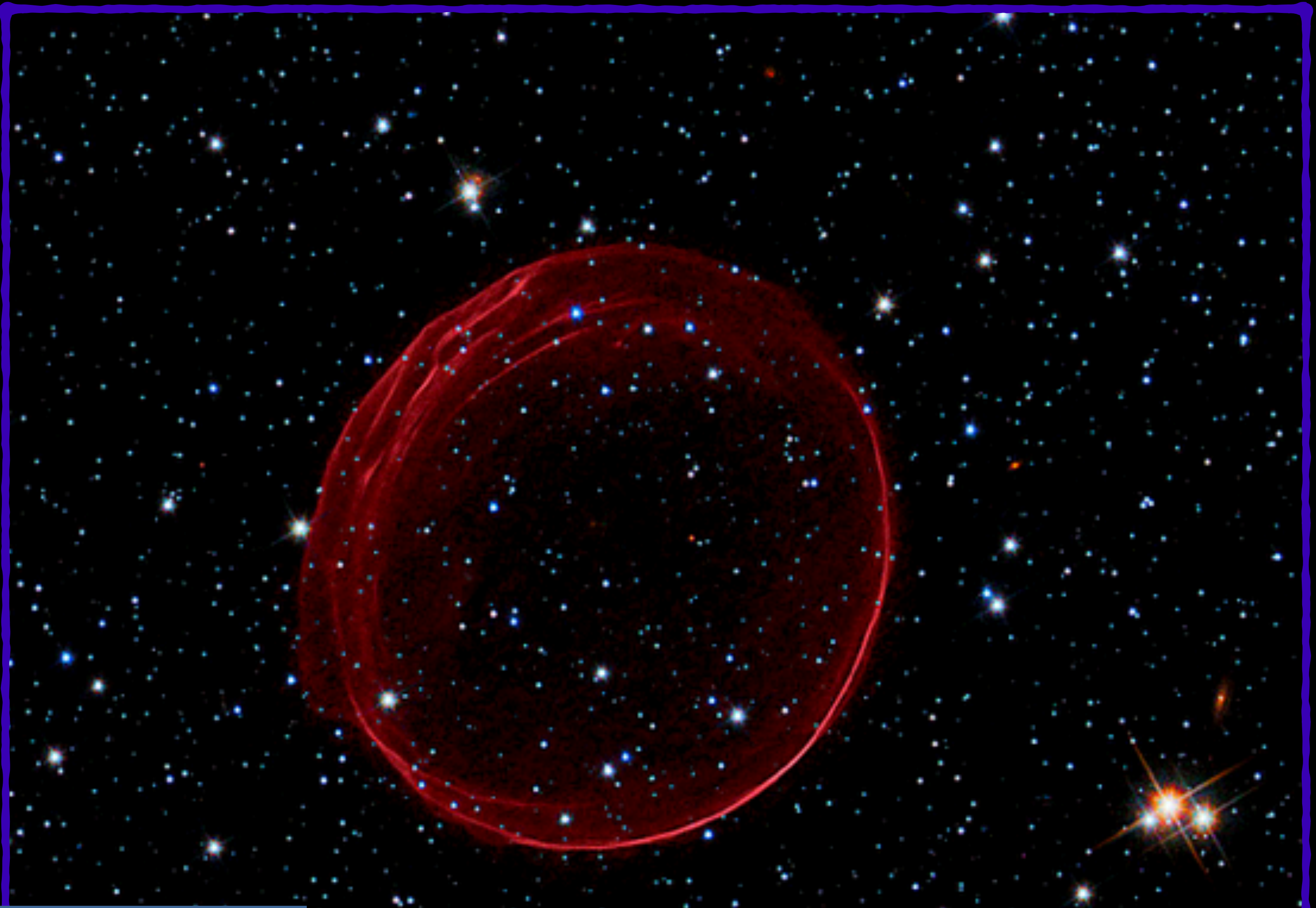
After learning all that, let's just enjoy the beauty of the thing.

Source: Stellar Winds Observatory at DSNM, Animas, New Mexico.

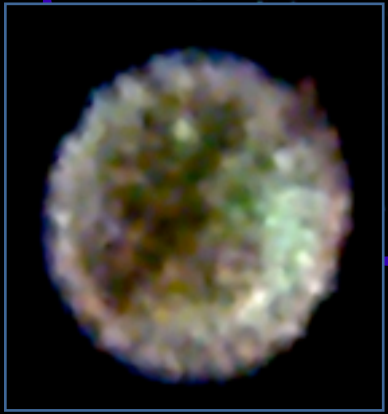
Why is this balloon in space so nearly perfect?

THE CUMBROUSLY NAMED SUPERNOVA BUBBLE SNR B0509-67.5 is one of the most comely serenities in the sky. Yet in space, even serenity is not what it seems. Only about 400 years old, this delicate bubble is expanding at over 5000 km/sec into a thin mix of gas and dust in the Large Magellanic Cloud 160,000 light years from Earth. That is an astonishing Mach 25,000 if the local sound speed is 200 metres per second or 1 km every 5 seconds typical for low-density interstellar gas, as it appears to be given the shell's smoothness. The dimples and layers on the upper left are density gradients whose compression ratio has been calculated as 12 times the base density of the gas into which the shell is expanding. High-pressure shock accelerates protons into high-energy cosmic-rays generated during the initial white dwarf SN1a detonation.

The delicate thinness of the shells suggests a low local gas-to-dust ratio comprising dust that is mostly granular silicon-based particles rather than porous carbon-based particles rich in water ice. There is scant evidence of blueish O-III emission in the 500.7 μm band but significant O-III, iron, and silicon emission in X-ray images (lower right). The wavy segments suggest that the local gas/dust density had already been perturbed by subsonic pre-SN waves passing through as the white dwarf and a red giant 'donor' star circled around each other before the explosion. All these data reinforce the notion that in astronomy great beauty can result when subtle and violent events occur in rapid succession.



Sources: Image: HST/ESA & XMM-Newton; Astrophysical data: Williams 2011.



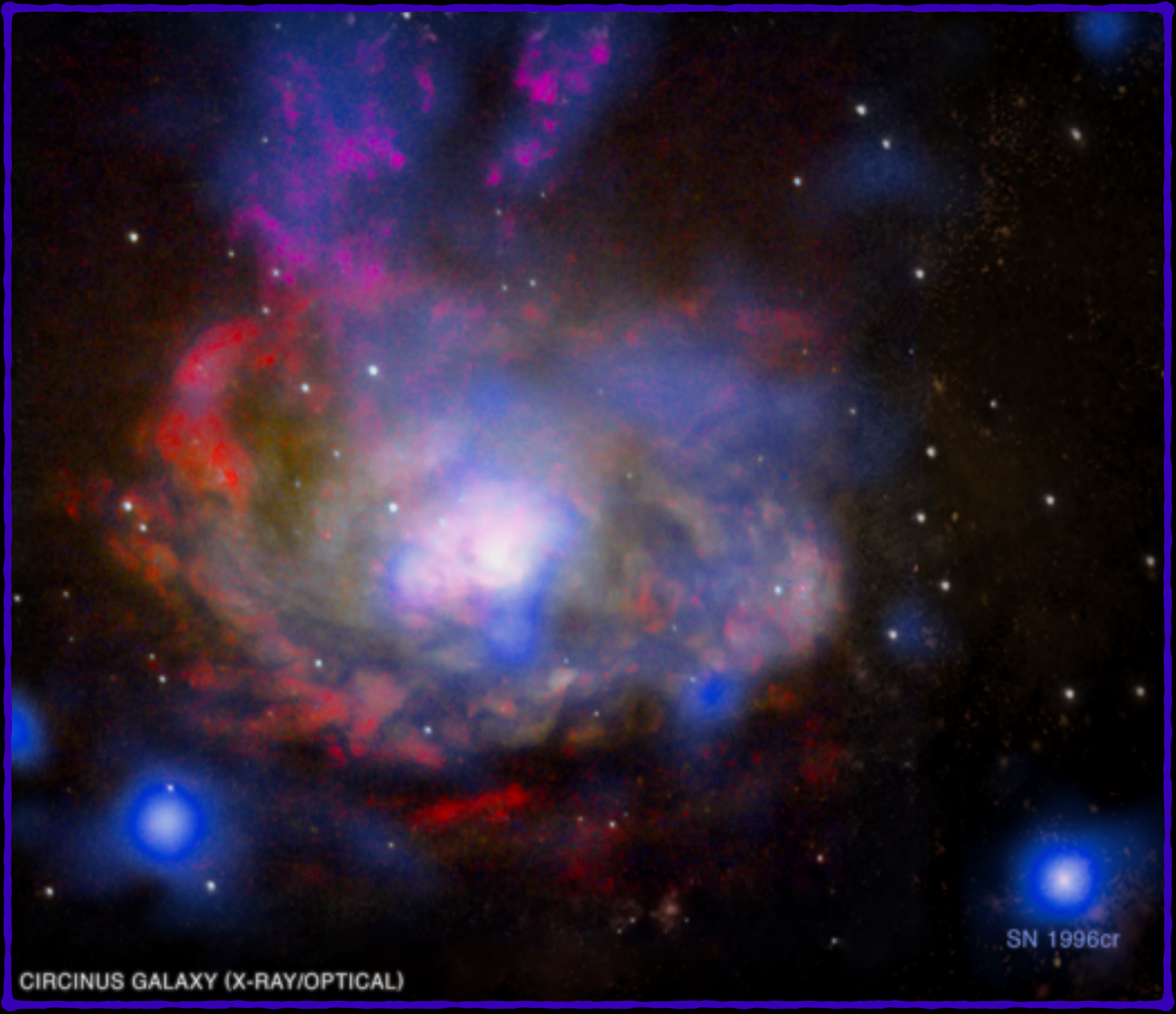
What the SNR looks like in Chandra telescope X-ray images.

Why did it take astronomers so long to spot this next-door neighbour?

Dimmed nearly to invisibility by the dust of our galaxy, the Circinus Galaxy is actually a next-door neighbour — only 13 million light years (4 Mpc) away. Although it is a bright Seyfert Galaxy with a fiercely fulminating core, it lies only four degrees above the Galactic Plane and is dimmed by five magnitudes of Galactic equatorial dust. (Five magnitudes means that it is 100 times dimmer than we would see it without the dust in the way.)

The few degrees on either side of the Galactic disc equator were.named the 'Zone of Avoidance' by the famed astronomer Edwin Hubble, who was cautious about the trustworthiness of data collected there. At magnitude 12.1, the Circinus Galaxy can be spotted in a six-inch telescope if observing from dark skies, but it lies in a field so rich with stars that it wasn't noticed until 1977. Even today it is seldom visited. For those who go to the trouble, Circinus is a meagre meal indeed: a faint oval patch six arcmins in length, with the barest hints of a spiral structure. It looks more like a planetary nebula than a galaxy.

In X-ray and infrared the tale is very different. In this Chandra/Hubble image we see what looks like a one-armed spiral. Closer examination shows hints of a bar structure and two arms massive with dust. It is also expelling large quantities of gas from the bulge region (a hallmark of Seyfert galaxies), which shows here as the mottled bluish streams above the bulge. Circinus is so obscure that it hosted a supernova in 1996 which wasn't even noticed for five years — and took another five to confirm.



How does a tiny dwarf galaxy like Henize 2-10 make so many stars?

Henize 2-10 is a dwarf galaxy about 30 million light years from Earth. It interests astronomers because it is similar to galaxies found in the early Universe.

Recent X-ray data from the Chandra X-ray Observatory in space and the Karl Jansky Very Large Array in New Mexico suggest that black hole growth may precede the growth of bulges in some galaxies. This has long been suspected but proof was lacking. This X-ray and radio image from the Chandra/KJVLA collaboration indicate that the black hole at the center of Henize 2-10 has a mass about one million times that of the Sun.

Stars are forming at a prodigious rate in this galaxy. The star clusters in the outskirts of the galaxy glow in blue, the signature of hot young stars. Since Henize 2-10 does not contain a significant bulge of stars in its center, this suggests that supermassive black hole growth may precede the growth of the bulge in this particular galaxy. Henize 2-10 is only about 30 million light years from Earth. Most nearby galaxies have well developed bulges and supermassive black holes growing in parallel. The reasons for Henize 2-10's antediluvian properties have yet to be fully constrained.

Hence this image provides astronomers with a detailed new look at how galaxy and black hole formation might have occurred in the early Universe. Optical data in this image from the Hubble Space Telescope shows in red, green, and blue. X-ray data from NASA's Chandra X-ray Observatory is in purple. Radio data from the National Radio Astronomy Observatory's Very Large Array is in yellow. A compact X-ray source at the center of the galaxy coincides with a radio source, giving evidence for an actively growing supermassive black hole with a mass of about one million times that of the Sun.

Source: *Chandra X-ray observatory.*

What hath 50 years wrought?

NGC 3432 is a feeble Magnitude 11.7 glimmer in Leo Minor

It is a difficult visual target when we search for it with a 6- or 8-inch backyard telescope because it is only 6.7 arcmin long and 1.5 arcmin wide.

When imaged through the Hubble Telescope (right) the galaxy becomes a rich jumble of reddish regions overlying a fainter blue glow in the background. Visually the object is such a muddle that even with the Hubble's trademark precision it defies a ready explanation. Reddish HII regions seem to form a shallow S from the upper right side to what appears to be an upward hook on the bottom left. These features suggest a vestigial spiral arm but there is such a thick overlay of dense HII star forming clumps throughout that it is difficult to discern the exact structure underlying it all. For example, if it is a spiral galaxy, which way is it turning? Which arm is nearest?

Back in 1966 when Halton Arp was examining the now-legendary National Geographic Palomar Schmidt Telescope plates that became what we refer to as the POSS plates, he thought this object was too deceptive to classify. He suspected magnetic fields might be involved, but in those days far less was known about the properties of magnetic fields on scales as large as galaxies. Fifty years later, we know a great deal that Arp did not know, yet he was right. Magnetic fields pervade entire galaxies, and profoundly influence events as momentous as multiple simultaneous starbirths.

Let us imagine ourselves looking over his shoulder as he was compiling his *Atlas of Peculiar Galaxies*. The very first paragraph of his Atlas is as apt today as it was then: 'Forty years after the discovery that galaxies were independent stellar systems, we still have not penetrated very far into the mystery of how they maintain themselves or what physical forces are responsible for shaping their observed forms. The galaxies are the constituent units of mass and energy in the universe, and yet we are still challenged by such questions as: What causes the characteristic shape of spiral galaxies? How are elliptical galaxies related to spiral? How are galaxies formed, and how do they evolve?'

We will read the rest of Arp's words on the next page, but for now, let's cut to the chase with Arp 206: We are looking at a big galaxy eat a little galaxy. Beautiful as it may seem, you are looking at a gigantic galactic banquet for one. Toothpicks, anyone?

Image: NASA/Goddard photo acquired by the Hubble Telescope 21 Feb 2020.

from the Atlas of Peculiar Galaxies, by Halton Arp, 1966

PREFACE

It is difficult to resist an oversimplified impression of what a galaxy is because the Hubble classification divides the galaxies into the well-known categories of smooth, amorphous ellipticals and flattened spirals with star-studded arms. But not all galaxies fit the schematic idealization of the Hubble sequence of nebular forms. In fact, when looked at closely enough, every galaxy is peculiar. Appreciation of these peculiarities is important in order to build a realistic picture of what galaxies are really like.

But the peculiarities are also important for another reason. If we could analyze a galaxy in the laboratory, we would deform it, shock it, probe it in order to discover its properties. The peculiarities of the galaxies pictured in this Atlas represent perturbations, deformations, and interactions which should enable us to analyze the nature of the real galaxies which we observe and which are too remote to experiment on directly. In general, the more conspicuous the peculiarity, the more illustrative it is of special events and reactions that occur in galaxies. Therefore the greatest deviations from the normal are emphasized in this Atlas. In some cases small peculiarities are included to illustrate, in sequence, how a certain type of peculiarity develops in importance until it dominates the form of the object. But it is from this overall range of experiments that we must then select and study the ones which will give the most insight into the composition and structure of a galaxy and the forces that govern it.

The present Atlas specifically started from an attempt to better understand spiral galaxies. Many analyses, often complex mathematical treatments have been made over the years, starting from the assumption that spiral arms were the result of tracks of stellar orbits moving under the gravitational influence of a central force field. I believe that the forms of spiral arms, their bifurcations and convolutions cannot be explained by such theories. In 1962 I undertook to assemble a series of photographs that would demonstrate this point. In the investigation of these spiral properties, galaxies which showed unusual or perturbed arms or filamentary extensions were sampled with high-resolution photographs with the Palomar 200-inch telescope. Subjects were first drawn from the pioneering work on peculiar galaxies by Zwicky and Vorontsov-Velyaminov. So many important objects emerged under high-resolution, limiting-magnitude study, however, that the investigation into the nature of spiral arms was postponed in order to systematically organize these new phenomena into groups and to publish a representative sample of the most significant objects.

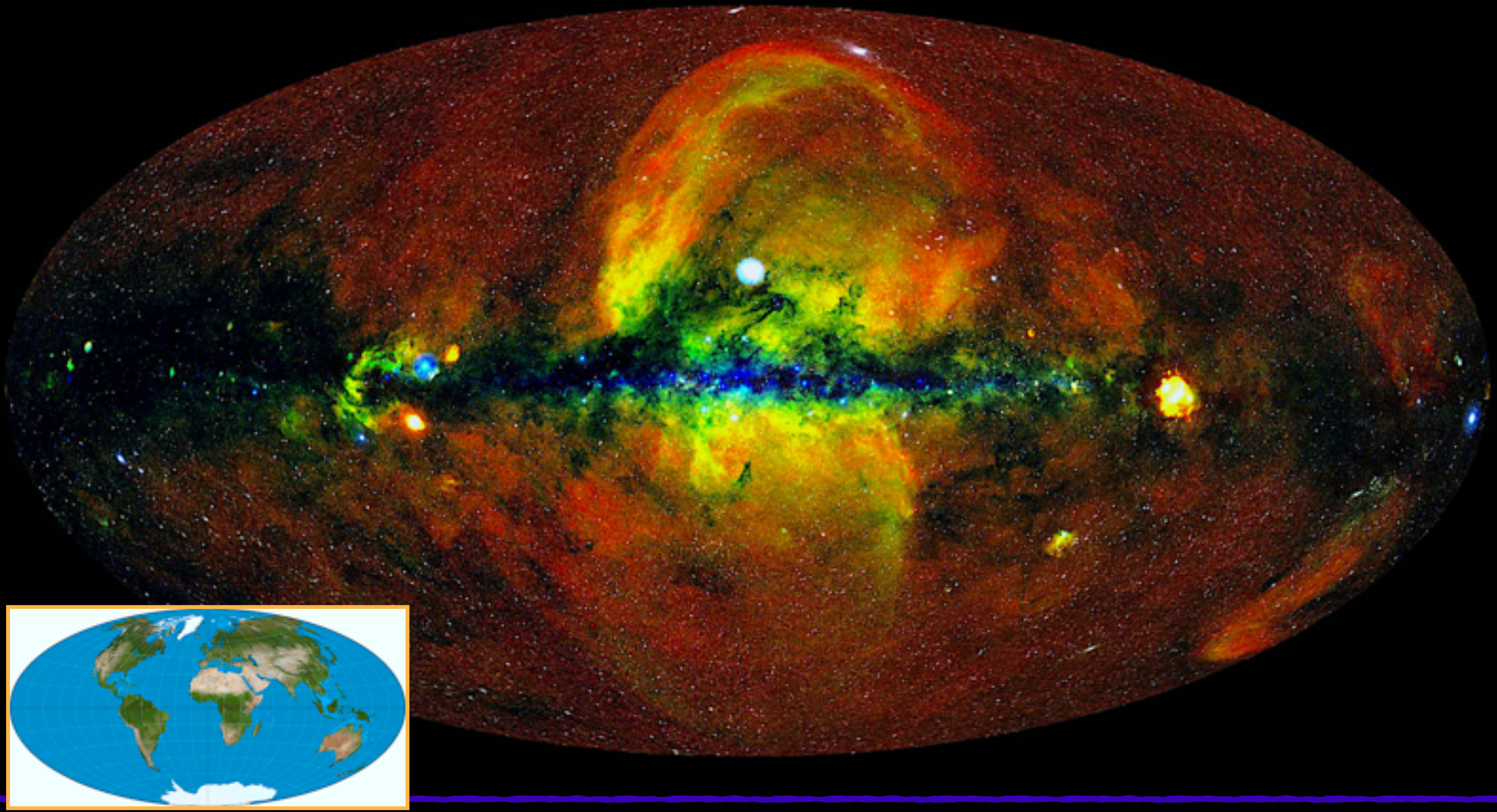
The Atlas as it has been realized in the following pages illustrates again that galaxies contain more than just stars, radiation, and gravitation. The pictures emphasize the importance of dust in some, they particularly imply a much more important role for the gas in general, and point to the existence of either new forces or forces which previously have been little considered. For example, if we consider galaxies to be merely an assemblage of mass particles, we should be able to treat them, in the limit, hydrodynamically as a frictionless fluid. But the twisted, distorted shapes and curious linkages pictured there suggest that viscosity-like forces are present. Dynamical friction does not seem sufficient because some of the filaments suggest a degree of viscosity approaching that of an elastic medium. Probably the only agency likely to account for this is that of magnetic fields that interconnect regions of wholly or partially ionized gas. Vorontsov-Velyaminov has stressed in the past the probable magnetic nature of some of the effects in peculiar galaxies.

Magnetic forces are very difficult to study optically, but are undoubtedly of great importance in our universe. Recent radio astronomy discoveries of violent events in galaxies reveal sources of energetic charged particles. These charged particles interact with magnetic fields and offer the hope of mapping, measuring, and understanding cosmic magnetic fields. The connection between the plasmas observed with the radio telescopes and the optical evidences of plasma effects pictured in the present Atlas is now open to us.

The overall aim of this Atlas is to present a number of examples of various kinds of peculiar galaxies. They are displayed in groupings that appear roughly similar, thereby furnishing also a rough, initial classification. Phenomena which each group represent may then be investigated by selecting the most favorable members in size or brightness, studying different members of the group in different orientations, and, finally, making some preliminary statistics of certain kinds of phenomena and their relationship to other observable parameters. It is hoped that this investigative procedure will not only clarify the workings of galaxies themselves, but reveal physical processes and how they operate in galaxies, and ultimately furnish a better understanding of the workings of the universe as a whole.

The source document is available in its entirety here.

The Flat Earth Society scores a point: 'Don't laugh at us, there is a Flat-Sky Society, too.'

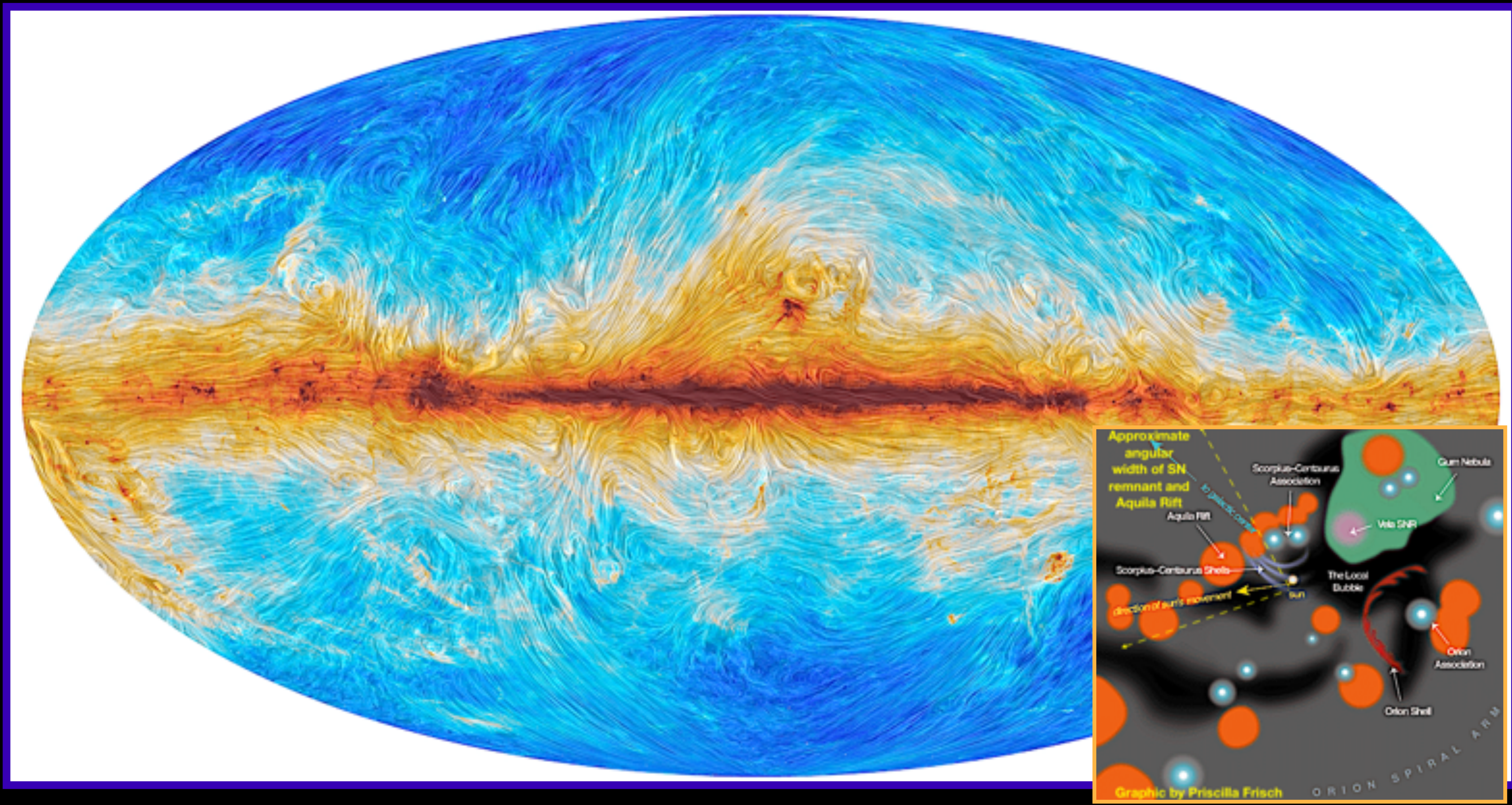


Molleweide projection of the Earth for comparison.

THE MOLLEWEIDE PROJECTION IN THESE IMAGES is often used to project a spherical view all around us onto a flat plane in such a way that all the data on the sphere are visible in one image that can be printed on a single page. Concessions have to be made when converting a sphere all around us to a flat page in front of us, and shape is one of them. To mentally turn the flat-sky Aitoff projection we see above back into a sphere, face the centre, reach out and grasp both side edges and pull them around till they meet in the middle behind your back. Imagine the result as a cylinder like a Mercator projection. Then curl the top & bottom of the cylinder inward till they join directly above and below you. You are back in the middle of a sphere.

The other limitation is that Molleweide projections can't show anything in 3D. A red 25th magnitude star 100 light years away or red 25th magnitude quasar 10 billion light years away can occupy two adjacent pixels and in this image we have no idea one was near and the other one far. Like it or not, this is a Flat Sky version of a Flat Earth.

The image on the previous page is the X-ray sky as recorded by the Rosita X-ray satellite. The image on this page is the magnetic field structure visible in the 353 Ghz radio band extracted by the Planck telescope and processed to show magnetic fields without distracting stars, nebulae, and galaxies. The misleading quality of a 2-D surface is evident in the huge arcs above and below the Milky Way. Those are *magnetic field flux tubes that loop into the outer reaches of the Milky Way disc*.



Graphic by Priscilla Frisch

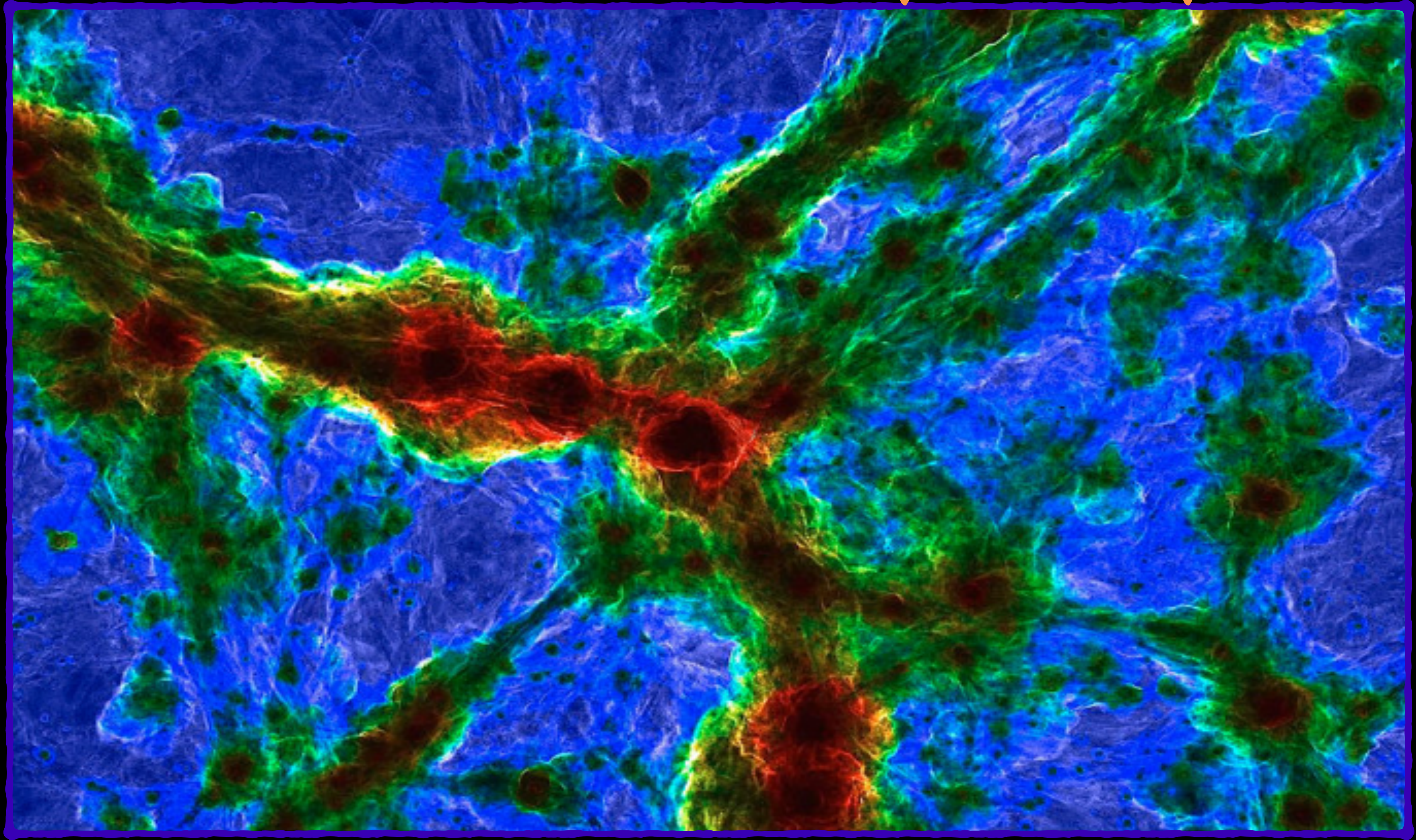
Why isn't IRAS 05437+2502 called Darth Vader's Ghost?

The little-known nebula IRAS 05437+2502 billows out among the bright stars and dark dust clouds that surround it in this image from the Hubble Space Telescope. It is located in the constellation of Taurus (the Bull), close to the central plane of our Milky Way galaxy. Unlike many of Hubble's targets, this object has not been studied in detail and its exact nature is unclear. At first glance it appears to be a small, rather isolated region of star formation. One might assume that the effects of fierce ultraviolet radiation from bright, young stars probably caused the brooding shapes of the gas. However, the bright, volcano-shaped feature may tell a more dramatic tale. The interaction of a high-velocity young star with the cloud of gas and dust may have created this unusually sharp-edged, bright arc is called a Herbig-Haro Object. It has the extraordinary velocity of 198,400 km per hour, which suggests it is a star that was ejected during a fierce 3-star encounter. Technically termed 3-body interactions, these are tales of celestial couplings gone awry. If a star blunders too close to a binary pair orbiting each other in celestial contentment, the resulting rather torrid interaction ends with the smallest of the three being hurled away at high velocity, while the remaining pair binds more tightly than before.

As for renaming at after the sinister Star Wars villain, you'll have to make an appointment with the International Astronomical Union (IAU). They are the ones in charge of names up there.

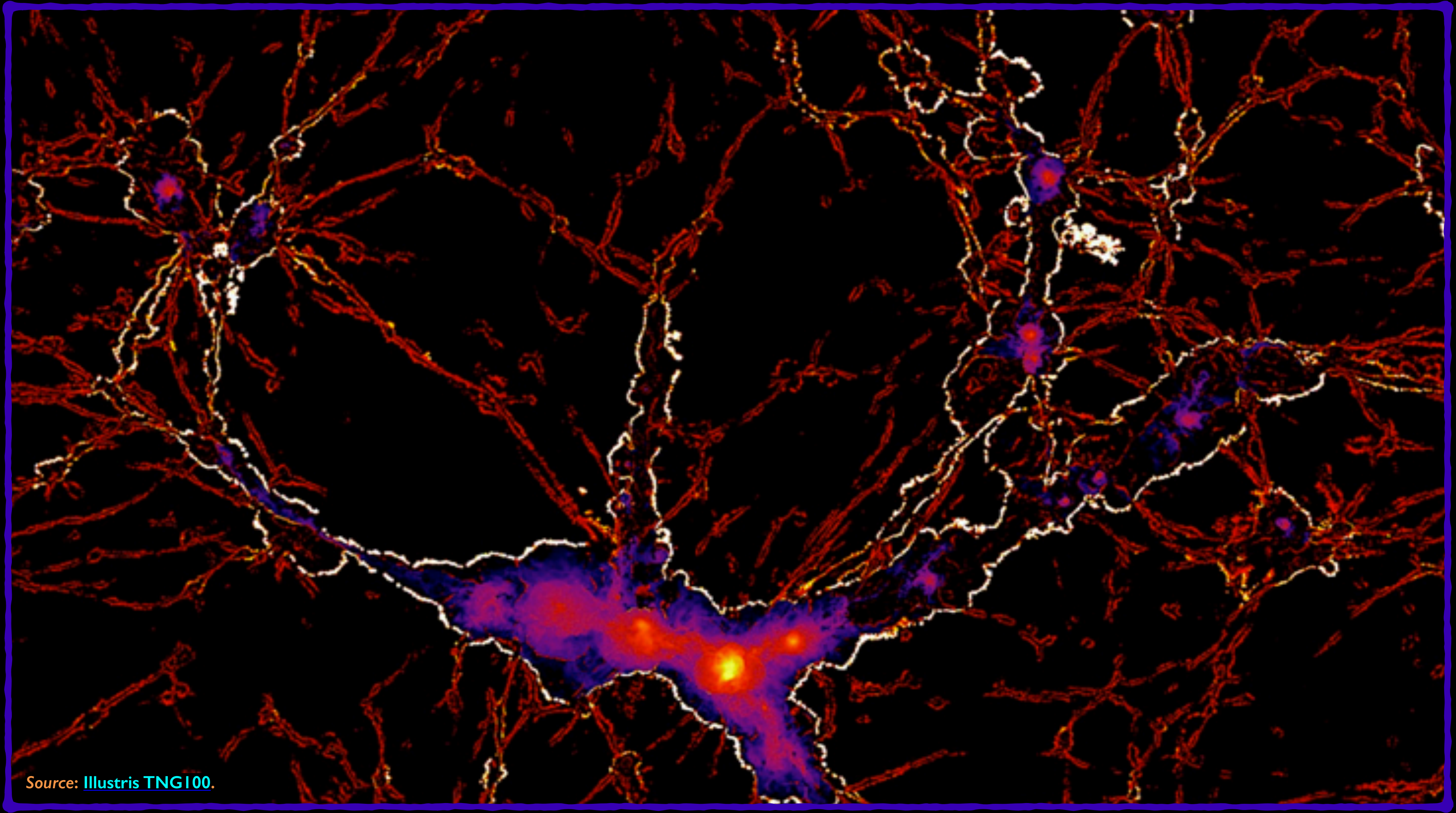
Source: NASA/HST

What does the Cosmic Web look like when you look only at its heat?



We cannot feel temperature in space by sticking our finger out a spacecraft window, even though intergalactic temperatures in scenes like the above range from 10 million degrees K upward. If you do stick your finger out a spacecraft port it will instantly freeze. Space itself is incredibly cold, only 2.725 degrees above absolute zero. The temperature of particles like hydrogen atoms or ion protons is measured by their kinetic energy (mass times velocity), which can rise to tens to hundreds of millions of degrees Kelvin. The kinetic energy of particles is thought of as heat, not temperature, because there are many cubic meters of cold space in between tiny individual particles. Particles acquire their kinetic heat from stars, supernovae, *magnetic fields*, and collisions with hyper-fast cosmic rays (relativistic protons). Once acquired the heat rarely cools because only colliding with another particle can reduce their velocity, and therefore kinetic heat. It can take billions of years before two particles actually hit each other. This *Illustris TNG 100 fullbox composite* shows shock mach number as the brightness of heat. The colour red indicates 10 million Kelvin gas at the centres of massive galaxy clusters. The brightest structures are shock-heated gas at the boundary between cosmic voids and filaments. *Watch this Illustris video of magnetic fields shaping gas flows in cosmic filaments.*

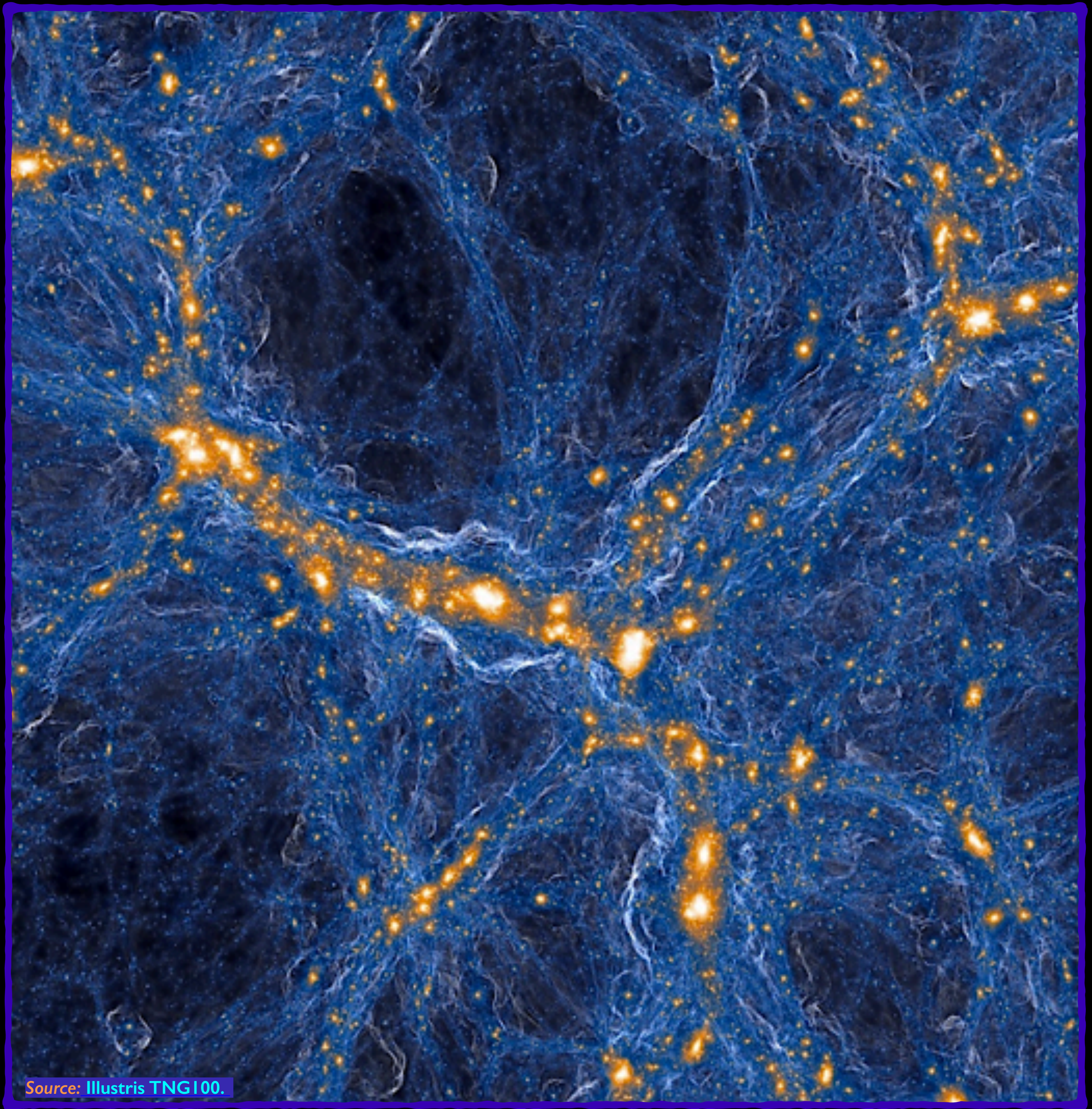
How can you stand still at mach 100?



Source: **Illustris TNG100**.

We CAN hear a scream in space! We just need the right ears to do it. Twenty octaves below our hearing range is a good target, but who wants ears like an elephant's? Mach speed propagates data across cosmological space just as it propagates data from the space between us and our hi-fi speakers. Mach 1 is the speed at which compression and rarefaction waves move through the local medium. The medium can be as dense as lead or as thin as hydrogen atoms in a cosmic void — roughly 1 atom in a sphere the diameter of you standing tiptoe with your arms raised straight up. In this image thin primordial hydrogen gas in bubble-like voids is pulled out of the voids by the gravitational attraction of ribbon-like cosmic filaments and clumpy galaxy superclusters like Virgo, Hercules, Perseus-Pisces, the Shapley Supercluster, and others even more remote. The outflowing void gas is supersonic compared with the dense gas in the filaments and clusters. As the gas enters the density gradient of the filament surfaces it slows down abruptly to the subsonic velocity that prevails just inside filament. The atoms' supersonic energy converts into thermal kinetic energy, or temperature. The glowing edges in this simulation are hydrodynamic shock zones – sonic booms millions of light-years long, which mark the boundaries between voids and reddish galaxy supercluster halos.

Why we spend money on astronomy: The more we look the more we see.



Source: **Illustris TNG100.**

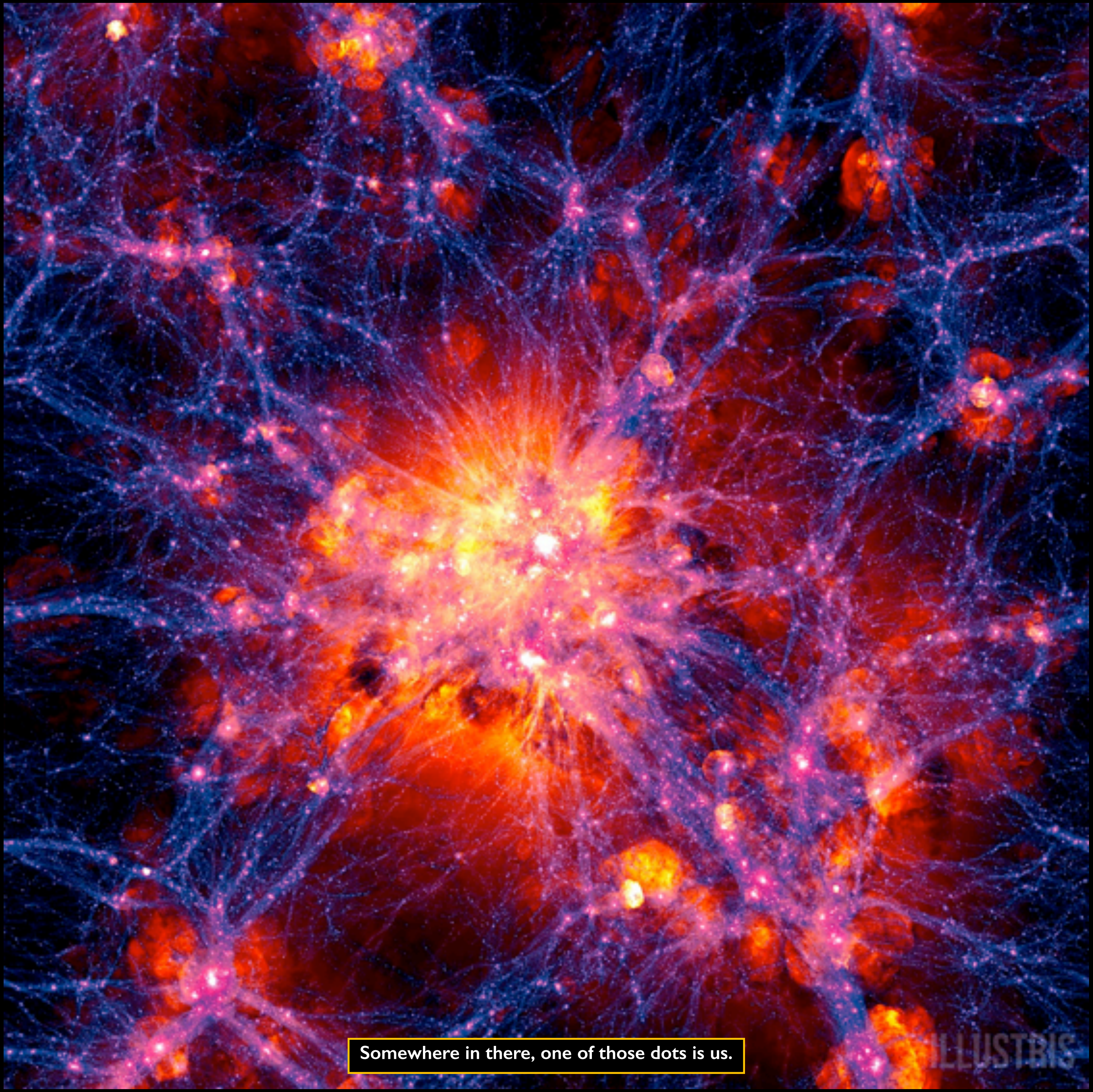
Our understanding of the *Cosmic Web* began with four landmark papers by *Yakov Zel'dovich* in 1965–80 on the subjects of *large-scale gravitational instability*, *magnetic inhomogeneity*, *shock waves at high temperatures*, and *adiabatic heating*. These set forth the basic properties of the Cosmic Web as we know it today. The Web became more complicated as equipment and theory improved over the next five decades. Today our picture of the Cosmic Web looks like the image to the left. The supposedly empty voids are in fact interlaced with gas filaments and modest-sized galaxy strings. Intercluster filaments are now seen to be complex highways of mainly spiral galaxies and primordial hydrogen gas funnelling fresh matter and energy into the beclotted nodes of galaxy superclusters, which are mainly ancient elliptical galaxies now no longer forming stars. The filaments have now been found to be rotating in helicoid tubes, a phenomenon that has yet to be fully explained—but which was *predicted in Zel'dovich's 1970 paper on magnetic inhomogeneity in the Cosmic Web*. The image to the left is a portrait of the detail and complexity of the Web as we know it today. The Cosmic Web looks remarkably like a neural network, and the physics of mass, energy, and time give the impression that we are looking at a life form that exists on time and sizes scales we cannot imagine.

FROM THE ILLUSTRIS WEBSITE:

Composite image of the full TNG100-1 box which overlays a projection of the dark matter density with the output of our on-the-fly cosmological shock finder, here used to derive the average mach number of shocks along each line of sight. All the gravitationally collapsed structures (in orange/white) are surrounded by successive shock surfaces (blue) which encode their formation histories

1611

Galileo's back-of-the-envelope drawings of Jupiter's moons


Somewhere in there, one of those dots is us.

TODAY

The envelopes have changed
and so have the sketches,

but they are still addressed
to the future.

And in case anyone asks, dark matter is not dark.

That big fuzzy thing in the middle is the Small Magellanic Cloud (SMC). The speckled ball its right is 47 Tucanae (NGC 104). The string of globby things leading left of the SMC is a thread of star forming regions torn loose by the SMC's last argument with its big brother, the Large Magellanic Cloud. Their fraternal hissy-fit some 300,000 years ago ripped an entire arm off the LMC, popped the LMC's bar off the galaxy's bulge by some 1,000 light years, and ram-pressure stripped most of the SMC's gas and splayed it across the sky all the way to Andromeda.

What the LMC–SMC collision did NOT do was remove any of either galaxy's dark matter.

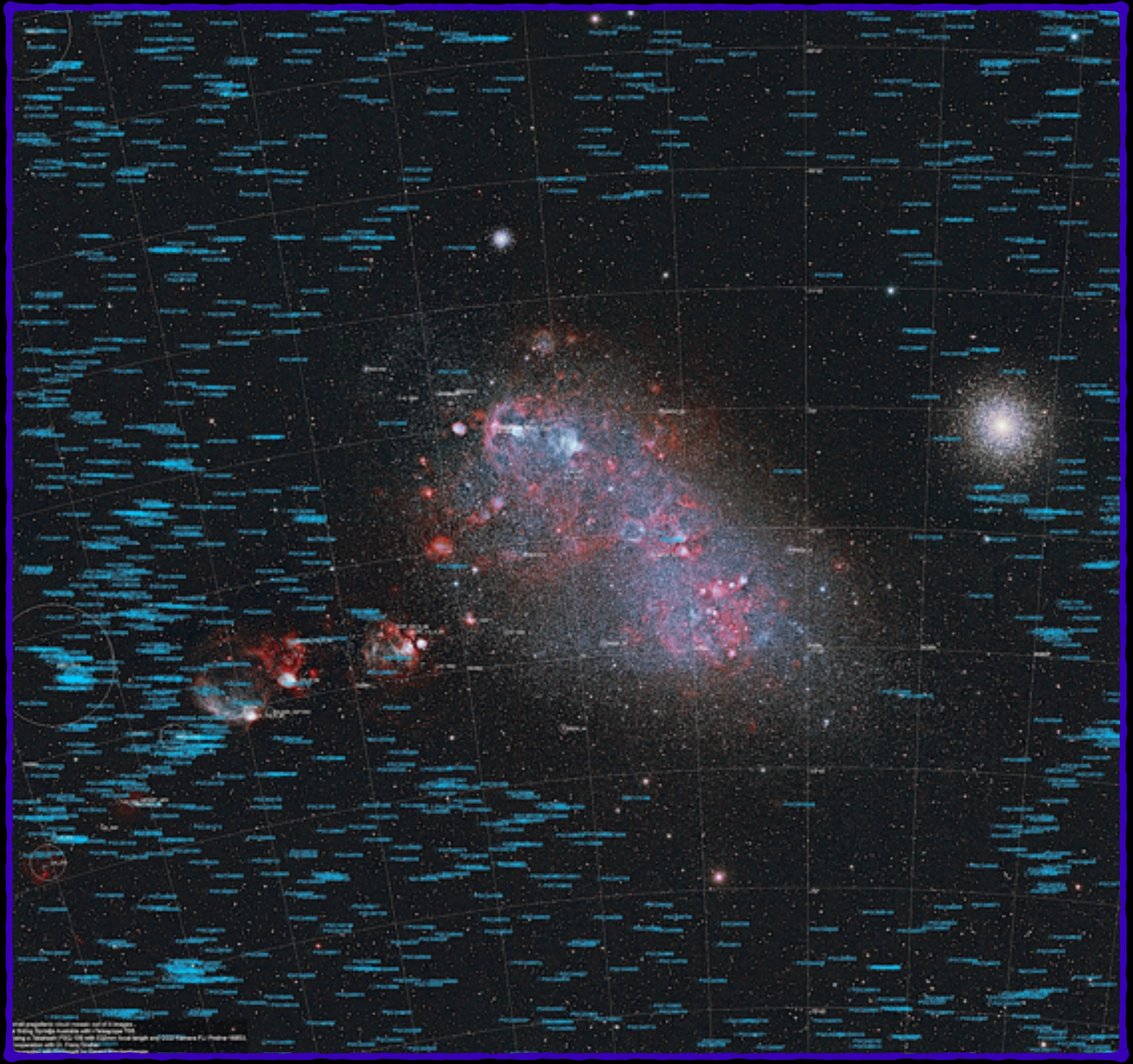
How do we know this? All those blue labels on this image are remote galaxies from the Uppsala General Catalogue (UGC) and Catalogue of Principle Galaxies (PGC). These galaxies pepper this image fairly uniformly—except near the SMC.

Galaxies are mostly dark matter we can't detect mixed with a small percentage of baryonic (atomic) matter that we do detect with admiring eyes every time we look up at night. So then … the dark zone around the LMC means that dark matter is dark, right?

Alas, no. The dark zone around the SMC is dark *DUST* that was once part of the gas-dust halo around the SMC. Every galaxy has a gas-dust halo, but dust is relatively heavy compared with gas. When the LMC stripped off the LMC's gas-dust halo, the dust decoupled from the gas and stayed bound to the galaxy. There is j-u-s-t enough of it to absorb the light of all those evanescently faint UGC and PGC galaxies we don't see here.

So, while it's true that dark matter is not dark (it is in fact invisible because it interacts with gravity but not light), this image shows quite nicely that dust sticks to galaxies a lot better than gas.

It is hard to imagine something massive that is not visible. That's why dark matter is one of the most interesting discoveries of recent astronomy.



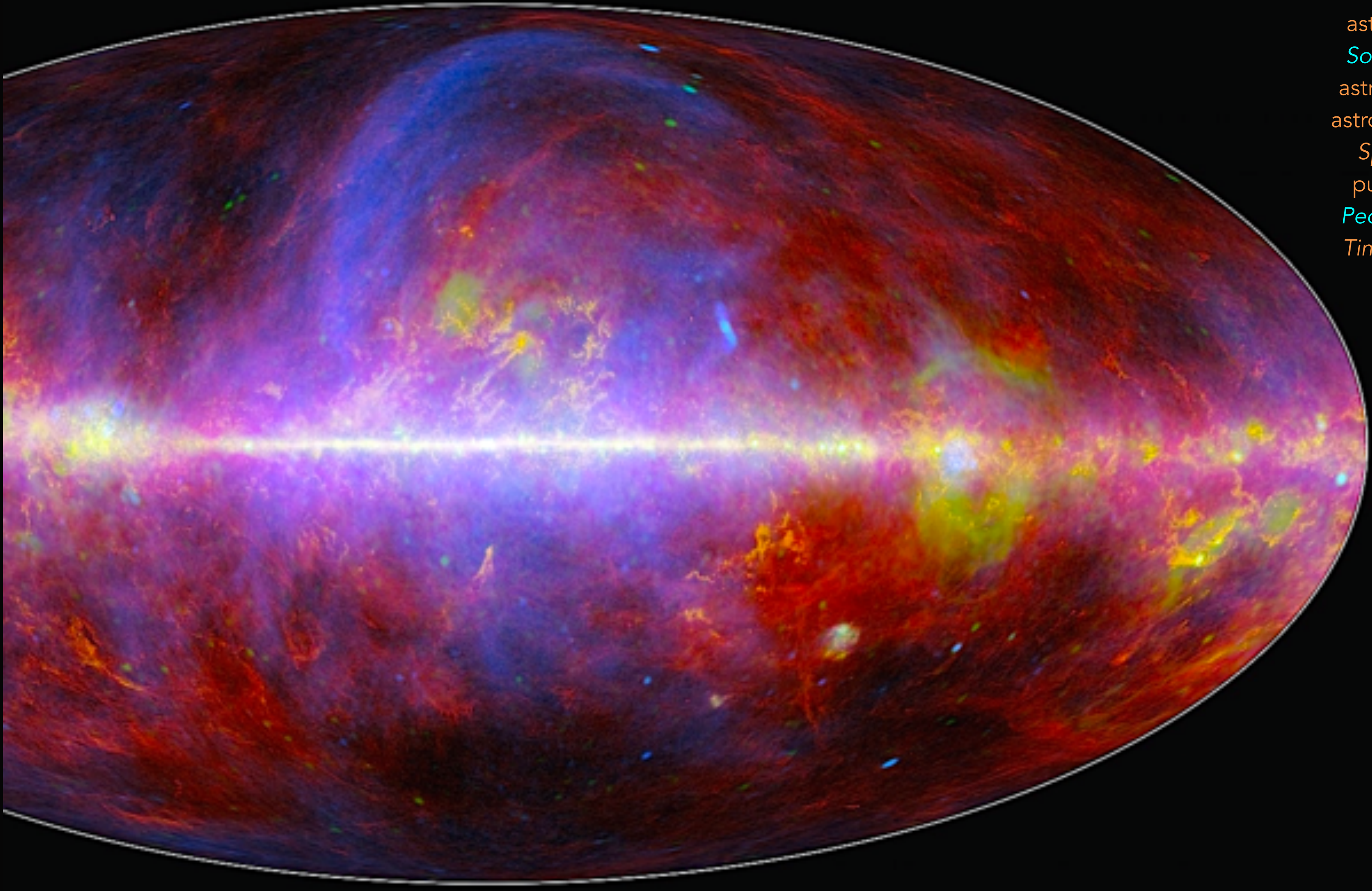
Every time we look up at night, there's something we haven't seen before.

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

Telescopes like this are the rings on which we string the keys of data sets, equations, algorithms, and information processing to unlock the hidden doors and opaque windows that conceal the truths underlying the universe. There are times when we fancy that we have discovered all the secret compartments, unveiled all the obscuring curtains, modelled the skeleton and flesh on which the cells and blood of the universe thrive. They look physical, but beyond them resides immeasurable heaven.

Welcome to the universe we cannot see

After decades of beautifully illustrated books about astronomy, it may come as a shock to learn that all along you have been seeing only one percent of the total light shining from all those resplendent stars, galaxies, and glowing nebula. If you could see the other ninety-nine percent of the electromagnetic radiation that floods the universe, the Milky Way would resemble the image below, made by the *2009–2013 Planck Telescope mission*. If the image below looks more like an art work, that is because it is — a masterwork called the Milky Way. *Sky Candy* is an art gallery of images taken by instruments that record gamma radiation, X-ray blazars, the glow of multiple bands of infrared, a universe filled with microwaves, the eerie hue of photons spinning long magnetic field lines. There truly is something new in the universe. Read about it here.



About the author

Douglas Bullis has produced over 30 published works in his 40-year career as a wanderlust writer. Born in the USA, he has lived for extended periods in Continental Europe, Sri Lanka, India, Malaysia, the Philippines, Crete, and now in South Africa. He produces the astronomy magazine *Nightfall* for the *Astronomical Society of Southern Africa*. He is an active hobbyist astronomer and has published over 40 articles in the astronomy forums *Cloudy Nights* and Australia's *Ice in Space*. His non-astronomy books include the just published memoire of his years in Crete, *Timeless People in a Changing Time* and a forthcoming book *Time and Timeless in Sri Lanka*, a journal describing the daily realities of life in a Buddhist society.

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