DECEMBER 2024
EDITION 6

MONOCEROS,
THE UNICORN

ASTRO DIGEST

STELLAR FUSION

UNVEIL THE SECRET OF STELLAR FUSION: THE COSMIC PROCESS FUELING STARS AND SHAPING THE UNIVERSE.

EARLY RED MONSTERS

DISCOVER THE ENIGMA OF EARLY MASSIVE RED GALAXIES—ANCIENT GIANTS THAT DEFY COSMIC GROWTH EXPECTATIONS.

NEUTRON STARS

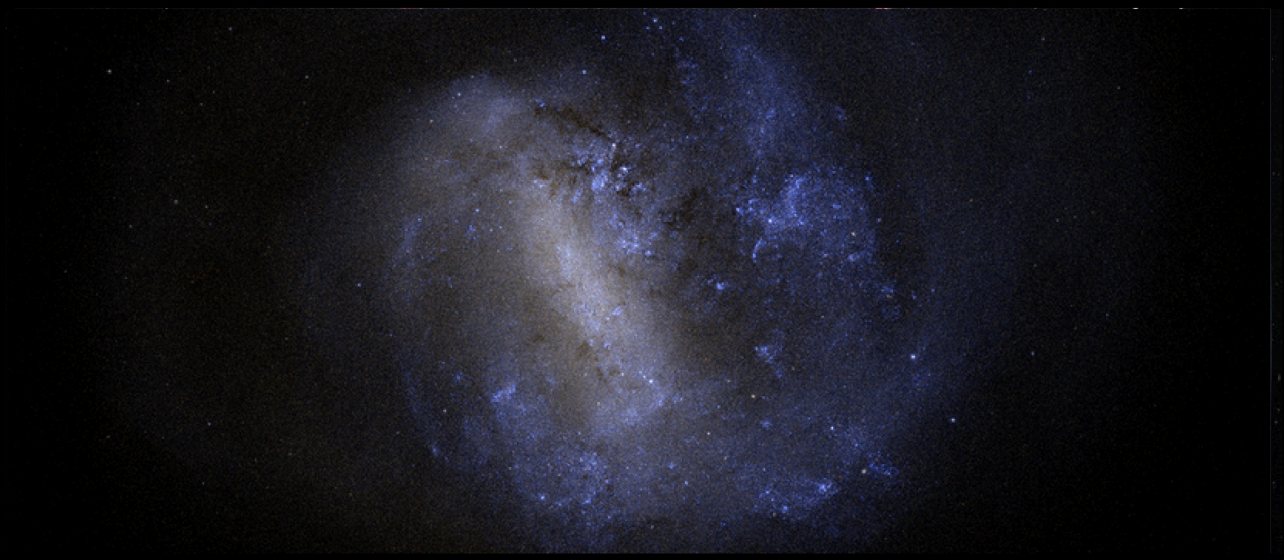
MUCH MORE COMPLICATED THAN AT FIRST GLANCE, EXPLORE THIS OBJECT STRAIGHT OUT OF SCIENCE FICTION.

TRIVIA

BECAUSE THE UNIVERSE LOVES TO KEEP US GUESSING!

EVENTS & STARGAZING

FEATURED STARGAZING LOCATION & OBJECTS



CONTENTS

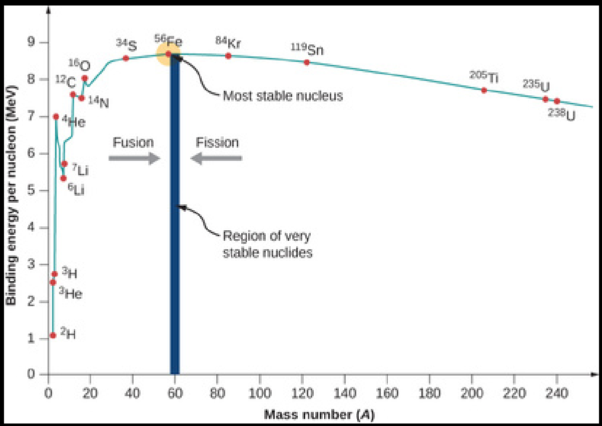
STELLAR FUSION

Stars burn, and they burn brightly. But have you ever wondered why and how they burn? If you have, you're in for a good read today. If you haven't, hopefully this will come off as informational. Moving on, we will split this article into 4 sections, and we'll start with the first section: The Why

<u>The Why</u>

Well, as you might know, stars originated from hot balls of particles that clump together due to gravity. And when enough of these particles coalesce and hit a certain point known as the Jeans Criterion, all this mass will undergo gravitational collapse and create a new protostar. This new protostar is young, bright, and excited. Now a hot ball of plasma, it starts to be able to do interesting things, such as fusing atomic particles together.

One might have heard of nuclear power plants, most of which utilise the power of nuclear fission, i.e. the splitting of big atomic nuclei to release energy. But did you know that the converse (fusing light elements together) can also release energy? In fact, the graph above shows the binding energy of each nucleon, and also pointers that show the transition from nuclear fusion to fission.



STELLAR FUSION BINDING ENERGY PER NUCLEON. CREDIT: PHYSICS LIBRETEXTS.

The graph of binding energy per nucleon for stable nuclei. Fusion of nuclei with mass numbers much less than that of Fe, and fission of nuclei with mass numbers greater than that of Fe, are exothermic processes.

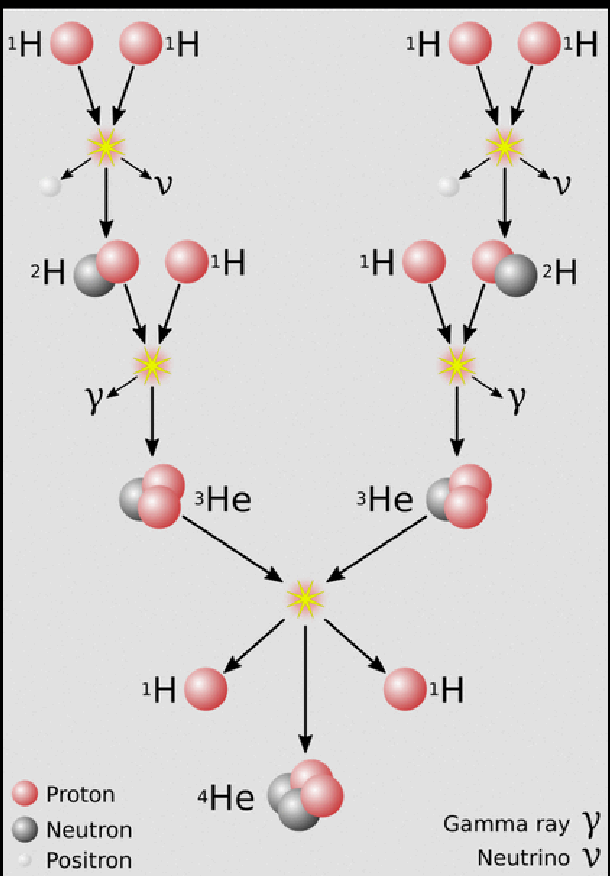
Nuclear fusion, however, is much harder to achieve. This is due to the fact that fusion only occurs at extremely high temperatures, while fission does not have that requirement. That is the main reason why us humans have yet to be able to produce large-scale fusion power plants, but these stars have no issue achieving these temperatures. With core temperatures up to millions of degrees Celsius, they have no issue churning out newly fused particles, and the first element that starts to fuse is Hydrogen. This fusion of Hydrogen atoms is known as Hydrogen burning.

STELLAR FUSION

<u>Hydrogen Burning</u>

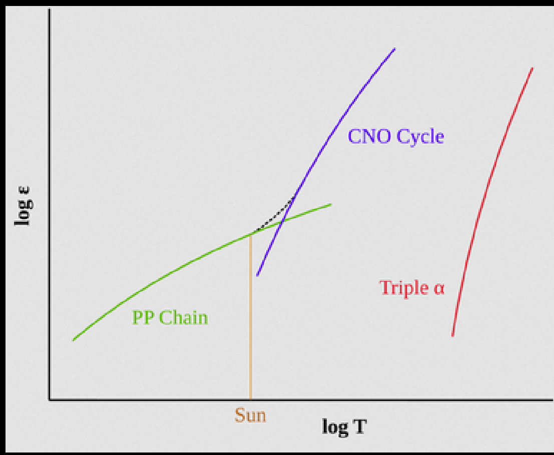
The pp-chain

The pp-chain takes in 4 Hydrogen nuclei and combines them through a series of reactions to form a He-4 nucleus. The complete reaction scheme is shown below, and it is normally the first process that stars use to start fusion, given that the pp-chain has the lowest ignition temperature among the three main reaction processes by stars.



PROTON-PROTON CHAIN. SOURCE: WIKIMEDIA

Graphic depicting the pp-chain reaction scheme.



FUSION REACTIVITY: WIKIMEDIA

Graph displaying the reactivity to temperature of different fusion processes.

Another thing to note is that deuterium fusion is actually the second step in the pp-chain, and this reaction occurs at around 10^6 kelvin. This step is rather vital for stars, as young protostars are able to accumulate more mass in this manner without starting hydrogen fusion (which has an ignition temperature of 10^7 kelvin) immediately, given that the core temperature would be controlled at 10^6 kelvin due to the deuterium burning.

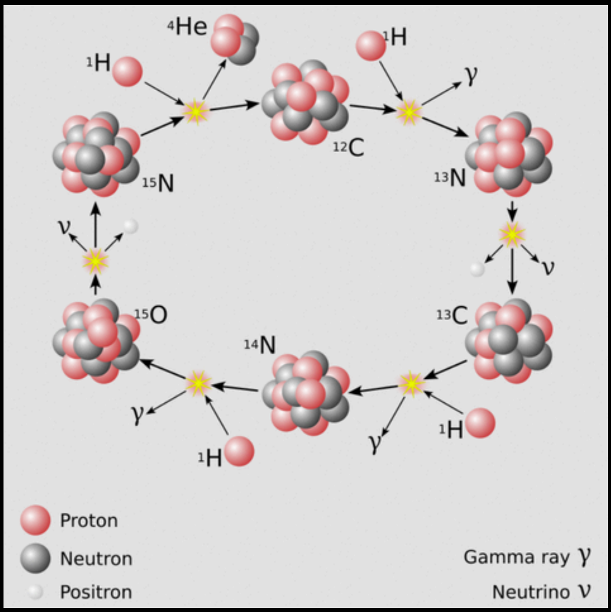
CNO cycle

The CNO cycle is a catalytic cycle, which means that there is a catalyst (something that facilitates the reaction without being used up by it) involved in the reaction.

STELLAR FUSION

In this case, the catalysts happen to be Carbon, Nitrogen, and Oxygen, hence the name CNO cycle. But unlike the pp-chain, this cycle actually has quite a few different ways of going about it.

The classic CNO cycle that most know of goes by the following schematic:



CNO CYCLE SCHEMATIC. SOURCE: WIKIMEDIA

While carbon, oxygen and nitrogen are not consumed in the reaction, they significantly speed up the rae of hydrogen fusion under the right conditions.

This version of the CNO cycle, also known as the cold CNO-I cycle (cold as this version of the cycle is limited by proton capture, and has a long timescale involved for conversion) is the most well-known cycle among the different possible cycles.

This cycle is also the only cycle that actually produces all three elements found in the name of this cycle, Carbon, Nitrogen and Oxygen.

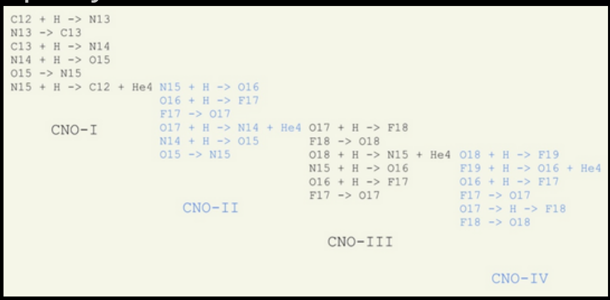
CNO-II, on the other hand, does not produce a carbon-12 atom and an alpha particle (i.e. He-4 nuclei) after the Nitrogen-15 step, but instead creates Oxygen-16. After this, Fluorine-19 is produced and then used up to give Oxygen-17, which goes through one more step to produce the alpha particle. To not overload this article with figures, schematics for CNO-II and the following versions of the CNO cycle will not be provided. But interested readers can feel free to research more about it online, where graphics are plentiful.

CNO-III and CNO-IV are only significant in massive stars, and CNO-III is an adaptation of CNO-II, while CNO-IV is an adaptation of CNO-III. Essentially what happens is that the Nitrogen produced becomes Oxygen instead. This might sound complicated, but the gist of it is that, to a certain extent, one can view the CNO-II, III and IV cycles as subsets of each other.

STELLAR FUSION

CNO-IV is a variation of III, which is a variation of II, which came from I. And the difference between the III and IV cycles is that in the IV cycle nitrogen does not appear after the part that it split off from the I cycle.

Actually, for the sake of illustration, I will attach a brief reaction scheme of all four cycles, which hopefully clears up any doubts.



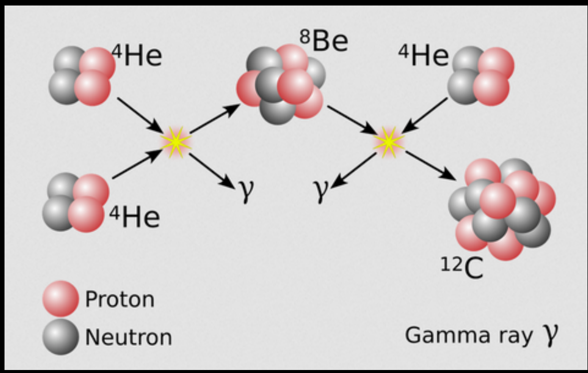
THE FOUR CNO CYCLES
Schematic showing the reactions for all 4 cold CNO cycles. Photons, electrons, and neutrinos have been removed for simplicity's sake

<u>Helium Burning</u>

Triple Alpha

Triple alpha is a process which uses three alpha particles to create a Carbon-12 nucleus. This process has two steps. Be-8, produced in the first step, is unstable and tends to decay back into the He-4 nuclei. However, if an extra He-4 nucleus hits this Be-8 particle before it decays, this can cause a reaction which results in a C-12 nucleus. Normally, such a reaction would be quite unlikely to occur.

But since the total energy of the He-4 nucleus combined with the Be-8 nucleus is almost the same as the energy of an excited C-12 nucleus, this resonance actually greatly increases the probability of this reaction occurring inside stars.



TRIPLE ALPHA PROCESS. SOURCE: WIKIMEDIA
Schematic of the triple-alpha process

<u>The End</u>

Keen-eyed readers might have realised from the graph earlier that this fusion process has a hard limit when stars reach iron fusion. This is because, after iron, energy is used rather than released to continue fusion, which means that this reaction is no longer thermodynamically favourable and will not occur. So, what's after this then?

Well, stars will start building up an iron core, which will eventually lead to the demise of the star.

STELLAR FUSION

This is because stars keep themselves from further gravitational collapse through fusion, which fights against the gravitational force. So when a star's rate of fusion is no longer able to keep up with its own gravity, a core-collapse supernova will occur and the dense core will become either a neutron star or a black hole, depending on mass.

But it is also important to acknowledge that only high-mass stars are able to reach the stage of iron fusion. Most stars, such as the Sun, will never be able to make significant amounts of iron to the extent that it leads to a supernova. Instead, they will enter the giant stage after they finish fusing hydrogen. Upon reaching the giant phase, they will shed their outer layers, revealing their cores. The layers will create a planetary nebula and the core will become a white dwarf.

EARLY RED MONSTERS

In yet another landmark find, the prolific James Webb Space Telescope has discovered a trio of ultra-massive galaxies, each consisting of about a hundred billion solar masses in the early universe, highlighted by Xiao et al. (2024) in Nature. These galaxies exist in the redshift range z=5 to z=9, corresponding to when the universe was only a billion years old. Images of these galaxies are available here.

At first glance, some may wonder about the significance of these three galaxies, given that the Milky Way itself is already 13.61 billion years old (corresponding to when the universe was roughly just 0.19 billion years old). The crucial difference is that the Milky Way was much smaller when it initially formed and gradually expanded to become the size it is today. In contrast, these galaxies were already as massive as the Milky Way is today during the universe's infancy, just 1 billion years after the Big Bang.

EARLY GALAXIES. SOURCE: NASA
Taken with JWST's NIRCam, this image shows various redshifted galaxies. This study considers three extreme examples of such galaxies.

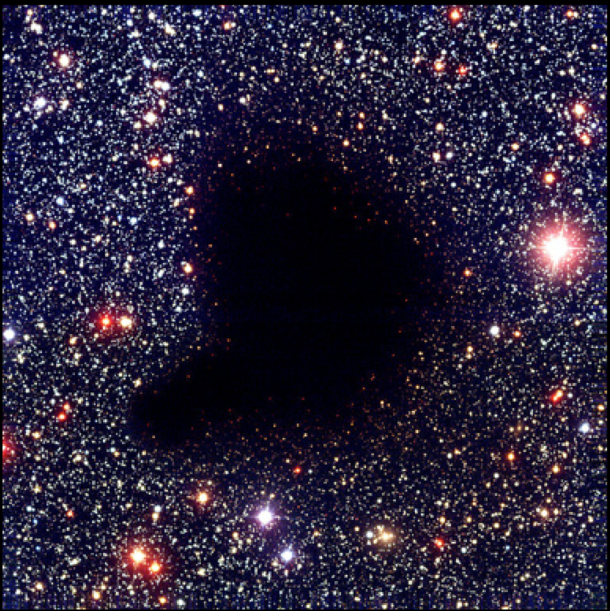
Not only are they much heavier than theoretical estimates for their epoch, but they also display an exceptionally higher star-formation rate than their other high-redshift counterparts. Xiao et. al. (2024) also reported that the baryon-to-star conversion efficiency for the three galaxies averages around 0.5, a value far exceeding the expected average for their redshift range. This efficiency highlights their ability to rapidly convert gas into stars, thereby further challenging current models of galaxy formation.

EXAMPLE OF A HIGH-REDSHIFT GALAXY. SOURCE: NASA
Another discovery by NIRCam was this galaxy. As of November 2024, it is the farthest galaxy to have been discovered, at a redshift of 14.32. In other words, the universe was only 290 million years old when the light was emitted.

Another question that comes to mind is: why is the emphasis on the "Red" -ness of these galaxies in the news?

EARLY RED MONSTERS

After all, don't all high-redshift galaxies look red, like the name suggests? The reason is that, while the three galaxies of interest are already red due to the stretching of their light by cosmological expansion, they are further reddened by the massive dust that constitutes them. In this context, dust does not refer to the same organic matter that makes up terrestrial dust, but instead to an interstellar version comprising elements heavier than helium, such as silicates or carbon-rich grains. This interstellar dust plays a significant role in reddening the light we observe.



RAYLEIGH SCATTERING BY BARNARD 68. SOURCE: WIKIMEDIA

A perfect example of observing dust-based reddening is a molecular cloud such as Barnard 68. Despite constituting only 1% of the molecular cloud by mass, the dust within it significantly reddens the light of background stars. This is precisely the mechanism by which the dust in the Red Monsters reddens their own galaxies' light.

The exact mechanism by which the light reddens via dust is labelled Rayleigh scattering. Via this process, dust particles cause shorter wavelength light to get much more scattered than longer wavelength light. Hence, along the line of sight to the galaxy, it will appear much redder than if there were no dust.

Interestingly, we need not look far into the early universe to see this phenomenon. It is easily observable from the comfort of your home - look no further than a sunset! The Sun's light reddens during sunset precisely due to a greater degree of Rayleigh scattering of the Sun's light by a thicker column of air.

RAYLEIGH SCATTERING BY EARTH'S ATMOSPHERE. SOURCE: DALL-E

Sunlight reddens during sunset, because its light approaches the observer at a shallower angle and has to travel through a thicker atmospheric column. This results in a larger degree of scattering of blue light.

EARLY RED MONSTERS

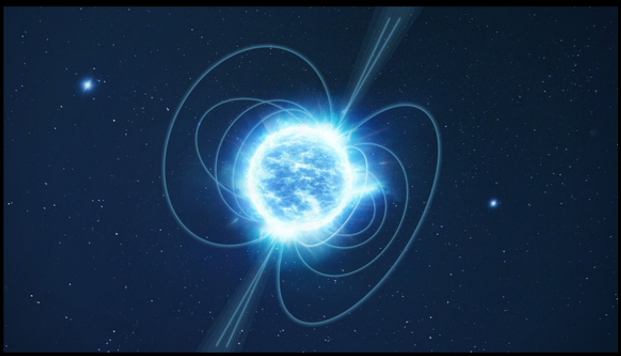
In summary, detecting these early “Red Monster” galaxies offers new insights into the early universe and challenges existing models of galaxy formation. More work is thus needed to understand the mechanisms driving galaxy formation, specifically those that allowed such monsters to form rapidly following the Big Bang. All we can say for now is that the conditions during the universe’s first billion years may have been far more conducive to rapid galaxy formation than previously understood.

Going back to the topic of galaxy masses, the discovery of such massive galaxies at a time the universe was relatively young challenges existing models of dark-matter halo formation and growth. In the prevailing model of galaxy and large-scale structure formation, it is believed that cold dark matter accumulated into clumps that served as the gravitational seed for normal matter to accumulate in. Given the larger-than-expected masses, it is possible that these different types of matter accumulated faster than the current models predict. This therefore raises the question whether modifications to the current understanding of dark-matter interactions or the nature of dark energy are needed.
Alongside these possible implications on our understanding of dark matter and energy, these galaxies could also help us better understand a key transition phase in the universe’s evolutionary history. This transition is the epoch of reionisation. This period marked the transition of the universe from being opaque to starlight to transparent as hydrogen was ionised by the formation of stars. You might be wondering - wasn’t the universe opaque when all the hydrogen was ionised, and then transparent after it cooled to form neutral hydrogen? The confusion lies in what light we are talking about when referring to opaqueness. When we say the early, pre-recombination universe was opaque, we mean that it was opaque to all wavelengths of light. This was because the universe was filled with densely packed ionised hydrogen, which scattered photons of all wavelengths. In contrast, when we say the pre-reionisation universe was opaque, we are specifically referring to its opacity to ultraviolet (UV) and shorter-wavelength light. This is because the first stars born during this period predominantly emitted light in these higher-energy wavelengths. To the long wavelength CMB radiation however, both epochs were more or less transparent. The Red Monsters observed happen to be at the very end of this epoch.

Regardless, further studies into these particular galaxies would provide a direct window into the conditions during the Epoch of Reionisation.

NEUTRON STARS

Neutron stars, the remnants of supernova explosions, represent some of the densest objects in the universe. With masses surpassing the Sun's, compressed into a sphere about 10-15 kilometers wide, these stellar remnants provide a unique laboratory for studying matter under extreme conditions. Among their fascinating properties is the presence of superfluid matter in their interiors.



NEUTRON STARS. SOURCE: ESA
An artistic depiction of a neutron star, showing the extremely strong magnetic fields that is generated by a neutron star.

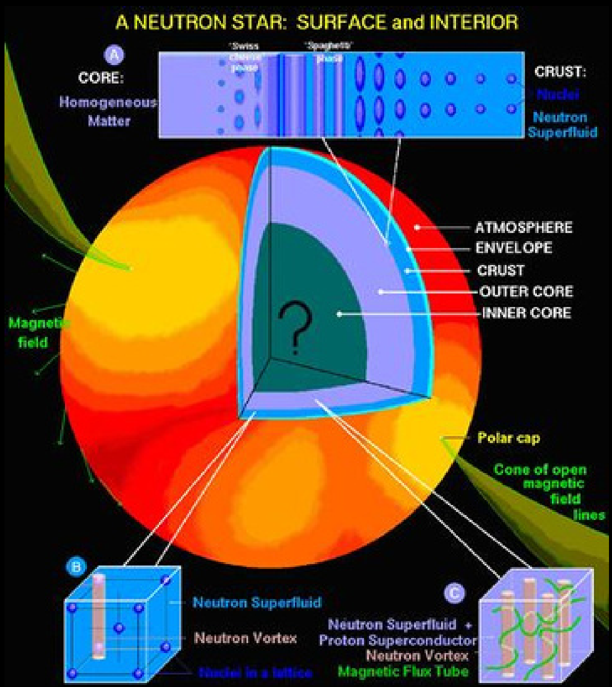
Superfluidity, a quantum-mechanical phenomenon, occurs when a fluid flows without viscosity. Within neutron stars, superfluidity arises in neutrons and, in some cases, protons due to extreme pressures and temperatures. These conditions facilitate the pairing of particles into a state described by the theory of Bose-Einstein condensation. Superfluidity plays a crucial role in explaining phenomena such as neutron-star cooling and rotational irregularities known as pulsar glitches.

Recent studies highlight the importance of neutron superfluidity in the crust and core of these stars. For example, researchers have identified "gapless superfluidity" as a possible explanation for delayed cooling in certain neutron stars, reconciling observational data with theoretical models. This state dramatically increases the specific heat capacity, slowing thermal relaxation after accretion phases in binary systems.

The interaction between superfluid neutrons and the crystalline crust of a neutron star is particularly intriguing. Vortices in the superfluid, which form due to the star's rotation, interact with the crust's structure. These interactions are thought to generate pulsar glitches—sudden changes in rotational speed. The dynamics of these vortices also influence the magnetic field structure, further impacting neutron star behavior.

Moreover, the "slab phase" of the inner crust, where neutrons form superfluid layers interspersed with nuclear matter, showcases unique quantum properties. This phase influences the overall superfluid fraction and contributes to the star's thermal and rotational evolution.

NEUTRON STARS



NEUTRON STAR STRUCTURE. SOURCE: UNIVERSITY OF SOUTHAMPTON

A depiction of the various layers constituting a neutron star. Note that the big question mark indicates a break down of our understanding for physics. It is as yet unknown what sort of matter constitutes the inner core of a neutron star,

The study of superfluid matter in neutron stars is not only advancing our understanding of these enigmatic objects but also shedding light on the fundamental physics of dense matter. These investigations bridge astrophysics and quantum mechanics, providing insights into phenomena that cannot be replicated in terrestrial laboratories

TRIVIA

Welcome to the Trivia! Here, we will include interesting facts and problems that we have curated for you, the reader.

The answers to the problems can be found in the next newsletter, but for now, we hope you'll enjoy this new segment!

Problem I

Locate the Christmas Tree Cluster (NGC 2264)

Source: Stellarium

Problem II

How much energy is released in Deuterium fusion? Namely, the reaction where Deuterium fuses with Hydrogen to produce a Helium-3 nucleus.

Fun-Fact-of-the-Month:

Rayleigh scattering, the same effect that makes stars and galaxies look redder, makes certain objects look bluer! Burning incense sticks produces a smoke that looks slightly blue in white light. This is because the red light scatters less and passes more through the smoke compared to blue light. This makes the smoke look bluer.

Source: Dall-E

ANSWERS FOR THE PREVIOUS NEWSLETTER

Problem I

Transit Limitations
-the planet's plane of orbit must align with Earth's line of sight to be able to capture the light-curve shifts from a transit
-for systems with multiple planets, the light curve might get messy and cause data processing to be difficult and less accurate
-high rate of false positives

Radial Velocity Limitations
-precision is impacted by distance due to apparatus limitations (requires high-signal-to-noise ratio)
-precision is also affected by multi-planet/star systems where there are more than two bodies at play
-only gives an estimate of the minimum mass

Transit > Radial Velocity when:
-size of the planet is a concern
-trying to analyse the planet's atmosphere

Radial Velocity > Transit when:
-eccentricity of the planet's orbit is a concern
-observing in low-mass star systems

Astronomers sometimes combine both methods to obtain data/confirm the presence of an exoplanet, as combined one would be able to pinpoint not just the size, but also mass, eccentricity and atmosphere of the planet.

Problem II

BAOs are essentially markers for large-scale structures, as these pressure waves would have caused an uneven distribution of mass that is only observable on cosmic scales, resulting in skewed distributions of cosmic landscapes that we observe now. With BAOs, one would be able to understand more about how galactic clusters come together and evolve, and gauge how much has changed from the early universe.

EOGs, on the other hand, give us information on stellar evolution since this region has rather low metallicity and gas density compared to other parts of the galaxy. The composition of the EOG is more similar to that of dwarf galaxies as well as the earlier stages of the Milky Way. By observing the EOG, astronomers are able to observe what stellar formation might be like in these conditions right here in our own galaxy instead of in other galaxies farther away.

EVENTS AND STARGAZING

Singapore Astronomy Symposium 2024
Date: Saturday, Dec 7, 2024
Time: 10:00 AM - 5:00 PM
Location: National Gallery Singapore
Admission: SGD 35
Join the Singapore Astronomy Symposium, a full-day event celebrating the wonders of the cosmos. This inaugural gathering features expert talks, interactive workshops, and stunning astrophotography displays, all designed to inspire astronomy enthusiasts of all levels.
Event Highlights:

- Keynote Talks
- Hands-on Workshops
- Astrophotography Gallery
- Solar Observing Session (Solar Cycle 25)
- Jupiter Opposition Viewing
- Networking Opportunities

Tickets close **Dec 6, 2024**. Don't miss this stellar opportunity!

Leavitt Lectures sign ups!

Given the new IOAA advisory regarding increasing inclusivity in future team selections as well as the low percentage of female participation in the Singapore Astronomy Olympiad, Astronomy.SG will comply by organising special lectures available for girls only to attend.

Tentative details of the Lectures are as follows, with further information available through the form below.
First lecture: 15 December (Sunday)
Last Lecture: 2 March (Sunday)
Held from 7:00 - 9:30 PM

Female participants of the 2025 SAO can register interest via this link: https://tinyurl.com/leavitt-lectures

For more details, feel free to email fish@astronomy.sg

We look forward to seeing you there!

EVENTS AND STARGAZING

Inaugural SAND Bingo Challenge

Join us for another round of our astrophysics-themed Bingo, where you can take on challenges and help your school collect points. With SAND 2025 still more than half a year away, there's still time to complete as many challenges as possible and aim for stellar prizes! The Bingo Challenge is still live on our Discord channel—come join the fun! Not sure how to enter? Just drop us an email/message and we'll get back to you!

Please note: This event is only eligible for secondary and tertiary schools that are open to participate in SAND 2025.

Featured Stargazing Location:
Upper Seletar Reservoir Park

Nestled in the heart of Singapore's natural beauty, Upper Seletar Reservoir Park is an ideal destination for stargazing enthusiasts. Known for its iconic rocket-shaped tower, the park provides an unobstructed view of the night sky. While its location makes it one of the best stargazing spots, we recommend visiting with a group rather than alone, given its remoteness. Whether you're a seasoned astronomer or a casual stargazer, the park's tranquil setting and open skies invite you to marvel at the universe's wonders. Bring along some friends, a small telescope or pair of binoculars, a cozy blanket, and let the night unfold its cosmic tapestry.

EVENTS AND STARGAZING

The month of December offers clear skies and a host of celestial sights. As the year comes to an end, new constellations and elusive objects become visible, offering fresh opportunities for stargazers. Whether you're equipped with advanced tools or simply using the naked eye, December’s skies have plenty to offer for everyone.

Source: Stellarium

Free-hand stargazing

- **Jupiter at opposition.** Jupiter’s closest approach to Earth will be on 7th December, and it will be closer, larger and brighter than it has been all year round. While it will be visible with the naked eye, its beautiful features are better viewed using binoculars or a telescope.

- **Geminid Meteor Shower.** In recent years, the Geminid meteor shower has become more prolific than even the famous Perseids. With the shower regularly producing over 100 meteors an hour under ideal conditions, this beautiful spectacle will be peaking on the night of 13th December and the early-morning hours of 14th December.

Source: Stellarium

EVENTS AND STARGAZING

Free-hand stargazing (Cont'd)

- **Full Moon.** Falling exactly in the middle of December (on 15th December), the full moon this month has earned the moniker 'cold moon'. Look carefully and you'll notice that it'll lie near the middle of a triangle formed by the 6th brightest star in the night sky, Capella, Jupiter and the stars Castor and Pollux in the constellation of Gemini.

Source: Stellarium

- **Ursid Meteor Shower.** The Ursid meteor shower will be active between 17-26 December and peak on the evening of 23rd December, through to the early morning hours of 24th December, where you will be able to witness about 10 meteors per hour. Despite the moonlight conditions, you should still be able to witness this stunning meteor shower.

Binoculars

- **The Fireworks Galaxy (Caldwell 12, NGC6946).** Adequately named as the fireworks galaxy due to its unusually high rate of star formation, NGC6946 is a spiral galaxy straddling the boundary

Source: Stellarium

EVENTS AND STARGAZING

Binoculars (Cont'd)
between the northern constellations of Cepheus and Cygnus. 9 supernovae have been observed in this galaxy in the past century, so you never know, you might just be able to witness one if you observe it in December!


Source: Stellarium

- **Caroline's Rose Cluster (NGC7789).** Called Caroline's Rose Cluster because it was discovered by German-British astronomer William Herschel's sister, Caroline, the loops of stars look like a pattern of rose petals from above when viewed through binoculars. This should make for a breathtaking scene when viewed through your binoculars!

Source: Stellarium

- **TX Piscium.** At a distance of 760 light years away from Earth, TX Piscium is one of the reddest stars ever discovered. With an absolute magnitude of -2.22, this variable red giant star can be found half a binocular width east of the circular cluster of stars found at the western end of the constellation Pisces.

EVENTS AND STARGAZING

Telescope

- **The Beehive cluster (M44).** With mostly white and blue stars with smaller ones that are red and orange, the Beehive cluster is packed full of beautiful colours. Containing about 1000 stars, it is one of the closest star clusters to Earth, 570 light years away in the constellation of cancer. Now is your chance to view this open, as it is best visible during the winter months using a telescope!

Source: Stellarium

- **The Horsehead Nebula (IC 434)**. A magnificent object located very close to the Orion nebula (it is in Orion's belt to be exact), the head of the horse is actually a separate nebula Barnard 33, pictured in front of a lot of hydrogen alpha gas, Although quite difficult to locate even with a telescope, it will be lit up by the bright star Altinak in Orion's Belt, so give it your best shot!

Source: Stellarium

SOURCES

Front page
Dall-E
Baryon Acoustic Oscillations - NASA Science

Content page
File:Large Magellanic Cloud rendered from Gaia EDR3 without foreground stars.png - Wikimedia Commons

Stellar Fusion
10.7: Nuclear Fusion - Physics LibreTexts
Proton-Proton chain
CNO cycle - Wikipedia
Triple Alpha Process | COSMOS

Early Red Monsters
Images of Galaxies
Barnard 68 image
High Redshift Galaxy image
Accelerated formation of ultra-massive galaxies in the first billion years
Red Monsters
Too many massive galaxies in the universe article

Neutron Stars
Neutron Star image
Neutron Star interior image
Gapless Neutron Superfluidity
Neutron-superfluid vortices
Superfluid fraction in the slab phase

Events and Stargazing
Binoculars in winter
Best meteor showers
Astrophotography
2024 astronomical calender
Zotti, G., Hoffmann, S. M., Wolf, A., Chéreau, F., & Chéreau, G. (2021). The Simulated Sky: Stellarium for Cultural Astronomy Research. Journal of Skyscape Archaeology, 6(2), 221–258. DOI: 10.1558/jsa.17822