AstroTalk: Behind the news headlines; August 2024

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Novel astronomical hardware solutions

It is often said that new developments in astronomy are technology-driven, particularly when we try to obtain funding to advance our research. While I was browsing through the astronomy-related press releases of the past few months, I was struck by a number of novel approaches to astronomical discovery that are indeed very closely tied to advances in technology. So for this article I decided to highlight some of the amazing innovations in the field.

My first example is from my own institution, Macquarie University in Sydney, Australia. Some of my colleagues here have pioneered a new technique for observing celestial objects during the day, potentially allowing around-the-clock visual monitoring of satellites and greatly improving safety on Earth and in space.

This reminded me of a demonstration I witnessed myself when I was a senior undergraduate student at a Dutch university. At that time, I had the amazing opportunity to travel to Chile and carry out observing programmes for the Dutch community on a dedicated 92cm telescope at the European Southern Observatory's La Silla Observatory. I got to know one of the other observers on the mountain, who operated the neighbouring Swiss telescope. And he introduced me to stellar observations during the daytime, which really blew my mind at the time!

The Macquarie University team's technique is different, though. It uses the University's Huntsman Telescope, a unique array of 10 (commercial) camera lenses working in parallel, originally designed for ultra-sensitive night-sky observations. The team recently demonstrated the Huntsman's ability to accurately measure stars, satellites and other targets when the Sun is high overhead, despite astronomers traditionally only observing at night.

> "*People have tried observing stars and satellites in optical wavelengths during the day for centuries, but it has been very difficult to do. Our tests show the Huntsman can achieve remarkable results in daylight hours*," says astrophysics Ph.D. candidate Sarah Caddy, who helped design and build the Huntsman Telescope.

Caddy worked with a team of Ph.D. students and staff to deploy the telescope, which celebrated its official opening at Siding Springs Observatory in the small rural community of Coonabarabran, in northern New South Wales, last year.

The telescope combines an astronomy camera and astro-mechanical focusing equipment with an array of 10 highly sensitive 400mm Canon lenses, oriented to all cover the same patch of sky.

Because the Sun washes out most light from other celestial objects, astronomers rarely observe during the day, but Caddy and her colleagues trialled special 'broadband' filters on a test version of the Huntsman telescope to block most daylight while still allowing specific wavelengths from celestial objects to pass through.

Their test version, a mini-Huntsman single-lens pathfinder telescope installed at the University's observatory in northern Sydney, allowed the team to assess various settings in a controlled environment without affecting scientific operations at the Huntsman Telescope.

The Huntsman's daytime capability allows continuous monitoring of certain bright stars that can be unobservable at night for months at a time because of their positions too close to the Sun.

One example is the red supergiant Betelgeuse, a nearby star around 650 light-years away in the Orion constellation in our galaxy, the Milky Way. Betelgeuse is of great interest to astronomers since the star dimmed substantially from late 2019 through 2020, likely because of a major ejection of gas and dust.

> "*Without this daytime mode, we'd have no idea if one of the brightest stars in the sky has gone supernova until a few months after its explosive light reached Earth*," says team leader Lee Spitler, Head of Space Projects at Macquarie University's Australian Astronomical Optics (AAO).
>
> "*We know Betelgeuse will blow up 'soon'* [in astronomical terms, this means anytime between now and millions of years into the future]*, but we don't know exactly when it will happen. For about four months of the year, it's only observable during the daytime because the Sun gets between Betelgeuse and the Earth at this time*."

The team's study confirmed that the Huntsman's daytime photometric data for Betelgeuse tallies with observations from observatories around the world, and even with space telescopes.

> "*This breakthrough paves the way for uninterrupted, long-term studies of stars like Betelgeuse as they undergo powerful eruptions near their end of life, expelling massive amounts of stellar material in the final stages of the cosmic cycle of rebirth*," says Spitler.
>
> "*Astronomers love it when stars in the Milky Way go supernova because it can tell us so much about how elements are created in the universe*."

Unfortunately, he adds, supernovas in the Milky Way are relatively rare—the last time it happened was in 1604.

> "*But when a supernova went off in a mini-galaxy next to our Milky Way galaxy in 1987, this was so useful for astronomers that they still observe the expanding supernova explosion almost 40 years later*."

Mastering daytime observation also delivers a big advantage in the rapidly expanding field of space situational awareness (SSA), which is the close monitoring of an ever-growing population of satellites, space debris and other artificial objects orbiting Earth.

More satellites will be launched in the next 10 years than in the entire history of human space exploration.

> "*With around 10,000 active satellites already circulating the planet and plans to launch a further 50,000 low-Earth-orbit satellites in the next decade, there's a clear need for dedicated day and night telescope networks to continually detect and track satellites*," says Caddy.

Potential satellite collisions have grave implications for communications, GPS, weather monitoring and other critical infrastructure.

Satellite photometry—an astronomy technique using optical telescopes to study changes in the brightness of celestial objects—can reveal valuable information, including the composition, age and condition of orbiting objects.

> "*Opening up to daytime observation of satellites allows us to monitor not just where they are, but also their orientation, and adds to the information we get from radar and other monitoring methods, protecting against potential collisions*," Caddy says.

Caddy's team demonstrated the Huntsman Telescope's potential for other astronomy observations requiring day and night coverage, including for monitoring satellites.

The team used the mini-Huntsman to refine techniques over many months, systematically investigating such factors as optimal exposure times, observation timing and precise tracking of targets even through atmospheric turbulence.

> "*Daytime astronomy is an exciting field, and with advances in camera sensors, filters and other technologies, we saw dramatic improvements in the sensitivity and precision achievable under bright-sky conditions*," says Caddy.
>
> Adds Spitler, "*We've refined a methodology for daytime observing and demonstrated it can be done on affordable, high-end equipment like the Canon lenses*."

The Huntsman Telescope has been constructed so that the 10 lenses work in parallel, feeding 10 ultra-fast CMOS camera sensors that together can take thousands of short-exposure images per second.

The attached camera can process images and manage very large data streams in an instant, using robotic control to track and capture fast-moving objects, and delivering continuous 24-hour monitoring of objects.

> "*Being able to do accurate, round-the-clock observations shatters longstanding restrictions on when astronomers can scan the heavens*," says Spitler.

"Daytime astronomy will be increasingly critical as we enter the next Space Age."

Daytime optical astronomy as a viable professional discipline, who would have anticipated that even a few years ago? If those developments didn't get you excited, wait until you read about my next subject: the latest developments of space-based astrophysics.

The future of space-based ultraviolet/optical/infrared astronomy requires ever larger telescopes. The highest priority astrophysics targets, including Earth-like exoplanets, first-generation stars and early galaxies, are all extremely faint, which presents an ongoing challenge for current missions and provides the 'opportunity space' for next-generation telescopes: larger telescopes are the primary way to address this issue.

With mission costs depending strongly on aperture diameter, scaling current space telescope technologies to aperture sizes beyond 10 m does not appear economically viable. Without a breakthrough in scalable technologies for large telescopes, future advances in astrophysics may slow down or even completely stall. Thus, there is a need for cost-effective solutions to scale space telescopes to larger sizes.

And so I came across the FLUTE project. This technology development aims to overcome the limitations of current approaches by paving a path towards space observatories with large-aperture, unsegmented liquid primary mirrors, suitable for a variety of astronomical applications. Such mirrors would be created in space via a novel approach based on fluidic shaping in microgravity, which has already been successfully demonstrated in a laboratory neutral buoyancy environment, in parabolic microgravity flights and aboard the International Space Station (ISS).

This technique has produced optical components with superb, sub-nanometer surface quality. In order to make the concept feasible to implement in the next 15–20 years with near-term technologies and realistic cost, we need to limit the diameter of the primary mirror to 50 meters.

Although the FLUTE concept has not yet been approved for construction, a so-called Phase I study has already been undertaken. The team explored their choices of mirror liquids, eventually deciding to focus on ionic liquids. Their detailed initial analysis has resulted in a detailed mission concept for a 50-m fluidic mirror observatory. Science fiction? Perhaps, but more science than fiction!

Perhaps more realistic in the short term is our search for "Earth 2.0" and the technology innovations required to achieve that successfully.

Searching for Earth 2.0 has been an obsession of almost all exoplanet hunters since the discipline's dawn a few decades ago. Since then, they've had plenty of technological breakthroughs help them in their quest, but so far, none of them have been capable of providing the clear-cut image needed to prove the existence of an exo-Earth.

However, some of those technologies are undoubtedly getting closer, and one of the most interesting uses a system called a multi-grated vector vortex coronagraph (mgVVC). Researchers think it may hold the optical properties to enable space-based telescopes like the *Habitable Worlds Observatory* (*HWO*) to finally capture the holy grail of exoplanet hunting—and it may be ready for prime time as early as next year.

That's the timeline provided by the project team for the Substantiating Unique Patterned Polarization-sensitive Polymer Photonics for Research of Exoplanets with Space-based Systems (SUPPPPRESS) project. Its primary focus for two years will be building and testing a mgVVC designed to eliminate one of the biggest challenges related to its implementation—polarisation leakage.

To understand why that's a problem, it's best first to understand what a vector vortex coronagraph is. A standard coronagraph uses some optical mask or physical disk to block out a star's light. This allows the light from that star's exoplanets to shine directly onto its optical system, allowing even relatively standard optics to make out details of the planet, like whether it has water in its atmosphere.

A vector vortex coronagraph uses a type of liquid crystal mask that shifts the phase of the starlight, essentially eliminating it. However, light from objects slightly off the mask's axis, such as an exoplanet, isn't affected by the phase shift, allowing it to pass through directly to the accompanying telescope's detector.

Polarisation leakage happens because of manufacturing defects in the liquid crystal mask used by VVCs. These could result from alignment errors, deformities in the liquid crystals, or stress or strain on the mask. Ironically, the way to fix this might be to make more masks.

The concept of a multi-grated vector vortex coronagraph is to layer multiple masks on each other. Since many of the defects are created in the manufacturing process, they should be unique to each individual mask, and as such, they shouldn't stack but cancel each other out when placed in series with one another. And the more grates there are, the more effective this solution is.

According to the team's latest insights, a single-grated VVC could capture light from an exoplanet that is about 10,000 times dimmer than its host star. In contrast, a triple-grated VVC would be capable of capturing light from exoplanets that are 10 billion times dimmer than their stars.

The quest for Earth 2.0 is clearly heating up!

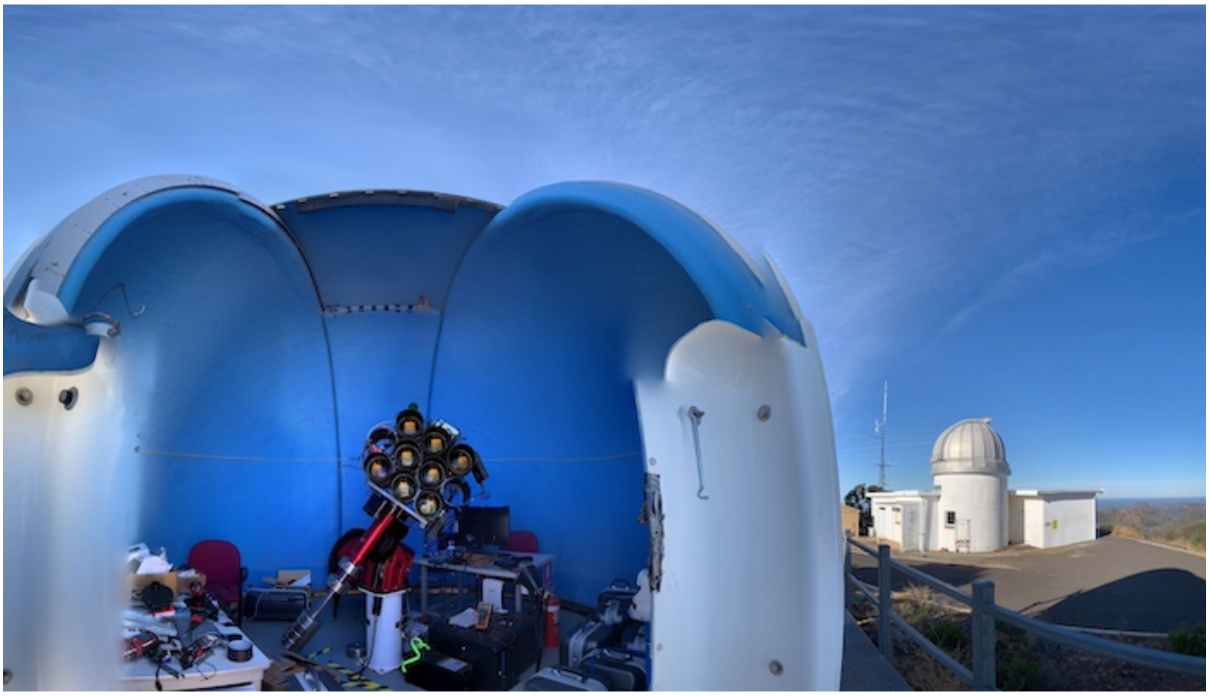

Fig. 1: Pioneering technology: Macquarie University's Huntsman Telescope observing space during the day

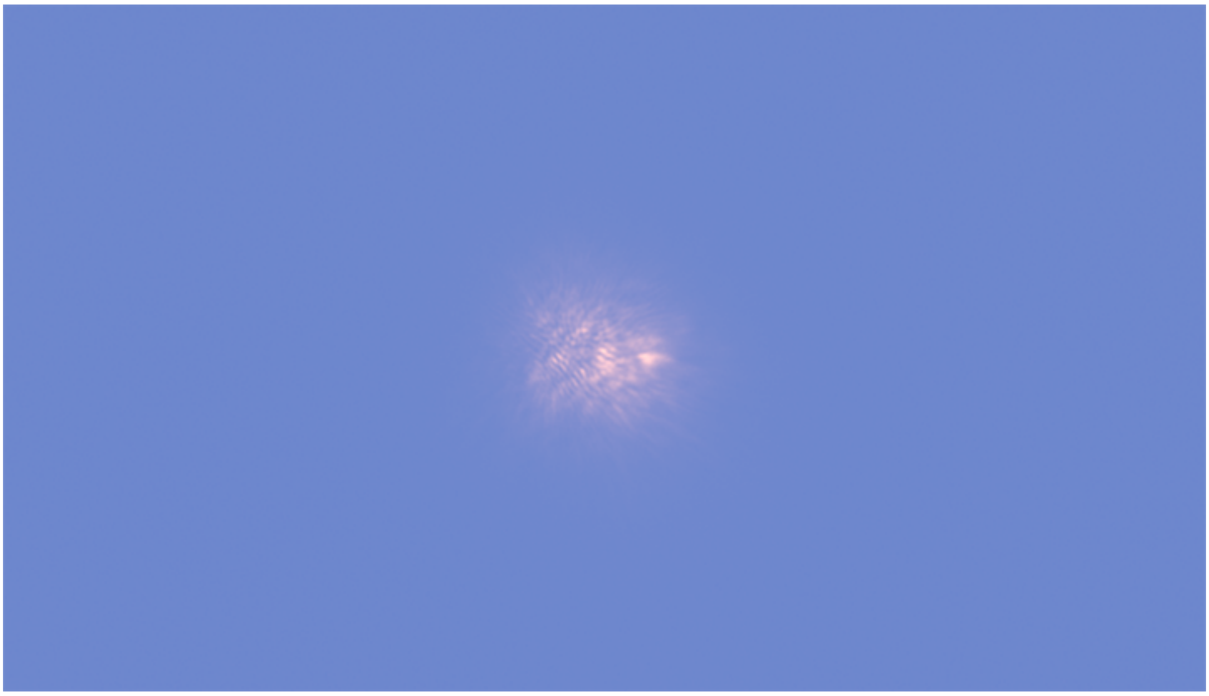

Fig. 2: The changing face of space: A daytime view of a nearby star Betelgeuse, located around 650 light years away

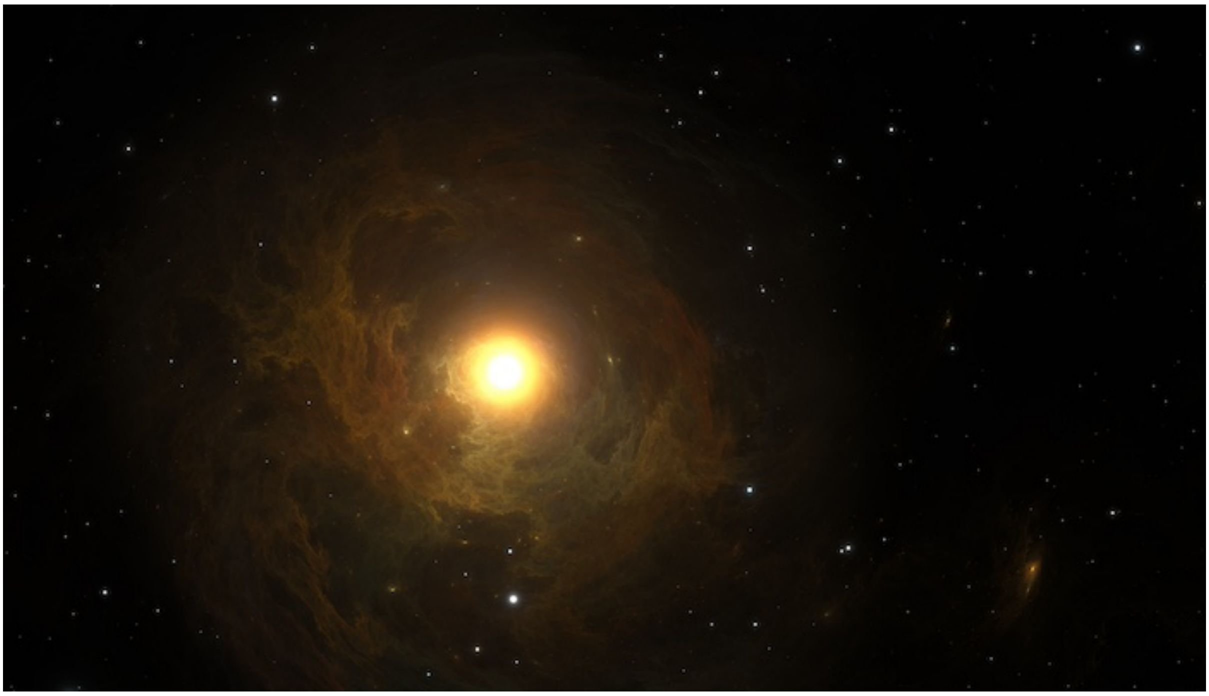

Fig. 3: The changing face of space: A daytime view of a nearby star Betelgeuse, located around 650 light years away

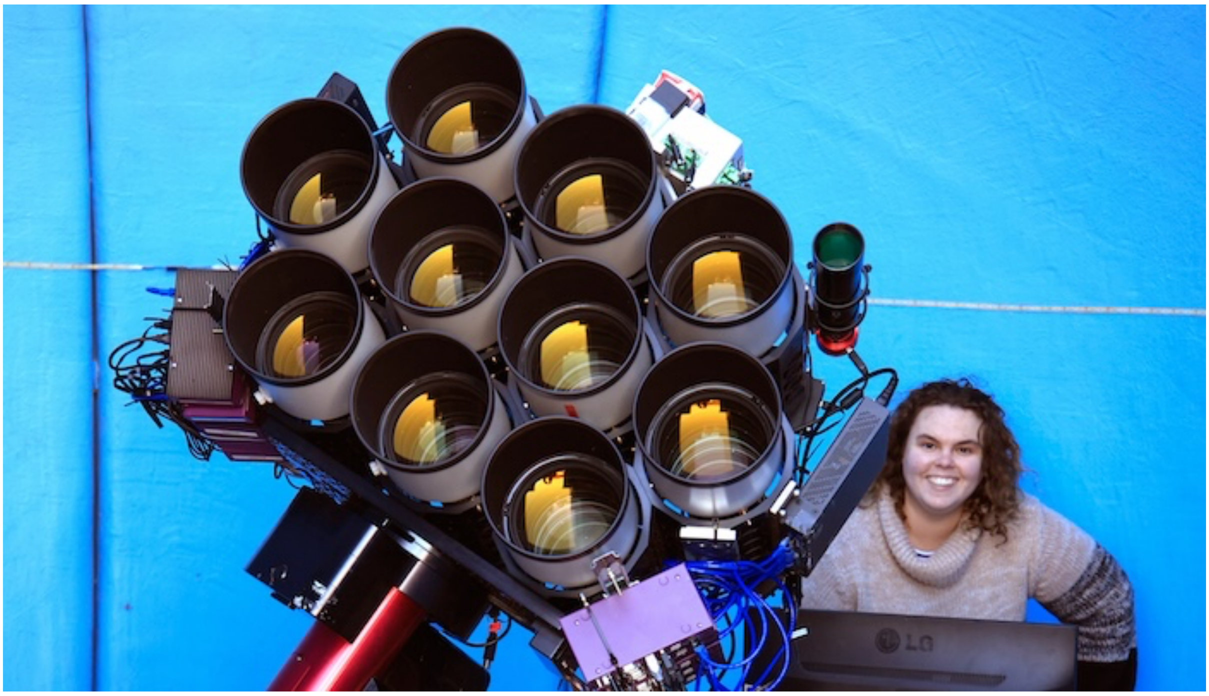

Fig. 4: Sarah Caddy with the Huntsman Telescope she helped design and build.

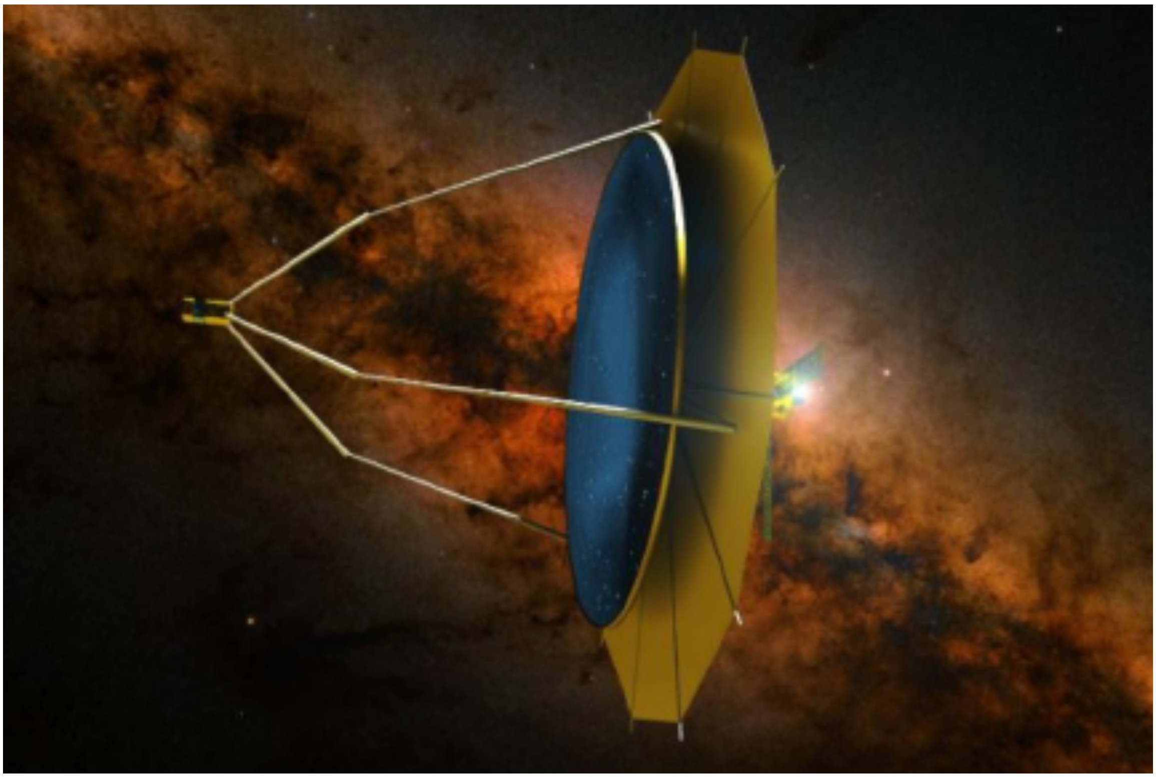

Fig. 5: Artist's depiction of the Fluidic Telescope (FLUTE) (Edward Balaban)

Fig. 6: FLUTE concept validation in microgravity conditions aboard Zero Gravity Corporation's G-FORCE ONE aircraft (Edward Balaban)

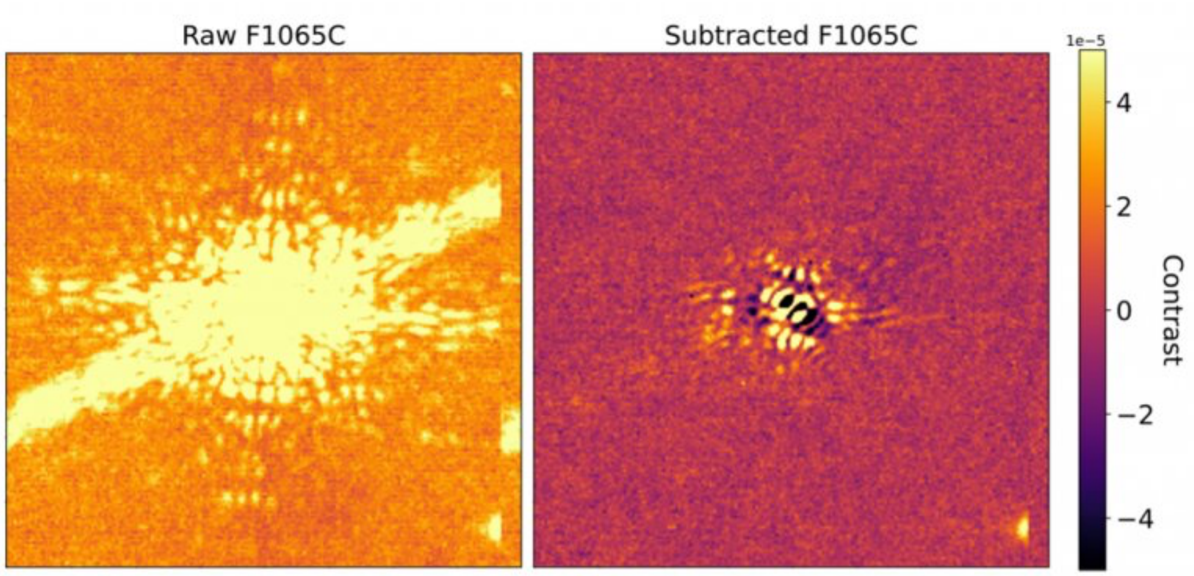

Fig. 7: How Webb's coronagraphs reveal exoplanets in the infrared (NASA)

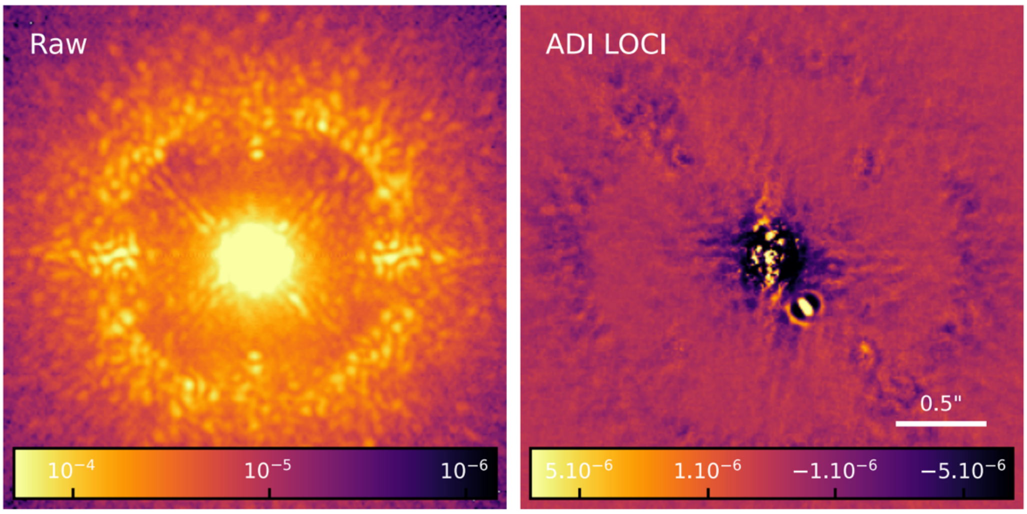

Fig. 8: Left: Raw coronagraphic image recorded by SPHERE/IRDIS with 2s exposure and dominated by a smooth halo at the centre and stellar speckles elsewhere. Right: Processed image of 200 raw coronagraphic images recorded with angular differential imaging. The exoplanet β-Pictoris b is located on the bottom-right of the star. Colour bars are in normalised intensity. — astro-ph.EP, https://astrobiology.com/2023/02/imaging-exoplanets-with-coronagraphic-instruments.html