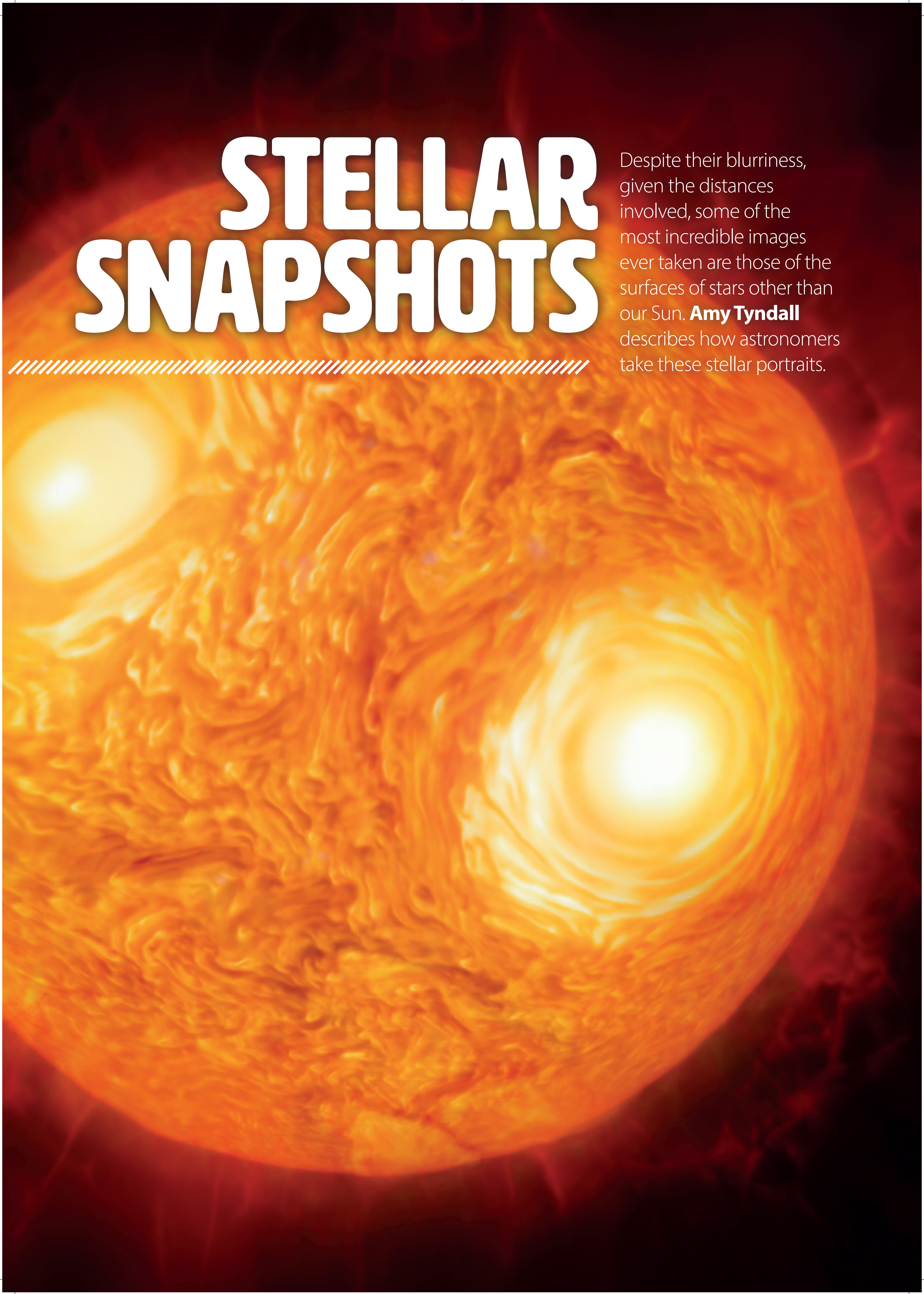
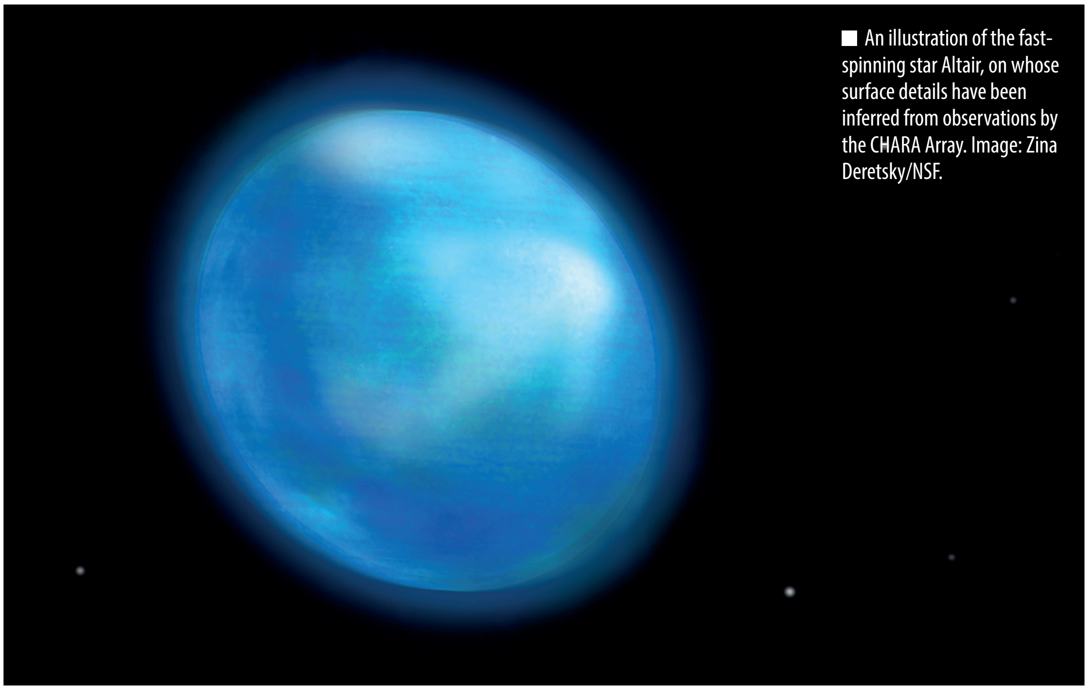
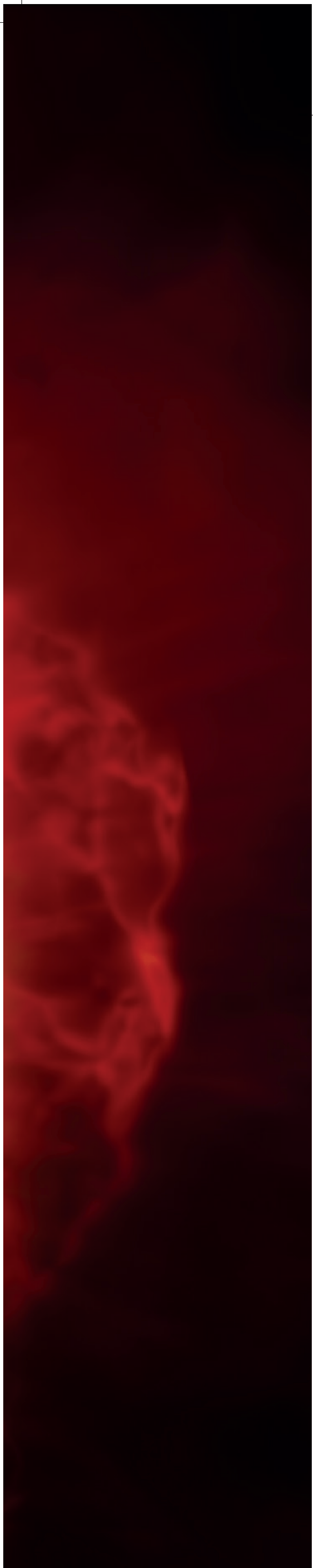
STELLAR SNAPSHOTS

Despite their blurriness, given the distances involved, some of the most incredible images ever taken are those of the surfaces of stars other than our Sun. **Amy Tyndall** describes how astronomers take these stellar portraits.





■ An illustration of the fast-spinning star Altair, on whose surface details have been inferred from observations by the CHARA Array. Image: Zina Deretsky/NSF.



■ An artist's impression of the surface of another star. Thanks to ingenious telescopic techniques, astronomers no longer have to rely on artwork. Image: ESO/M. Kornmesser.

IMAGES of the Sun are now so detailed you can almost see the churning movement of pockets of plasma on the surface, and easily imagine its intense heat. It is the only star that we can see with such precision. There are hundreds of millions of other stars within our Galaxy, most at distances so vast that they will only ever appear as small pinpricks of light against the darkness. A select few, however, are large enough and bright enough for our largest telescopes to resolve them, not as dots of light, but as small discs. The ability to see fine detail at this point is then dependent on several factors, including the size of the telescope and the particular wavelength of light being observed.

Even with a new generation of giant telescopes under development, such as the 39.5-metre European Extremely Large Telescope (E-ELT), few stars appear large enough on the sky to be imaged in any great detail. For example, to resolve the disc of the nearest star, Proxima Centauri, 4.2 light years away, one would need a telescope mirror almost twice that of the E-ELT. A mirror two kilometres in diameter would be required to get a nice snapshot of its orbiting planet. How do astronomers get around this? The answer lies in some telescopic teamwork.

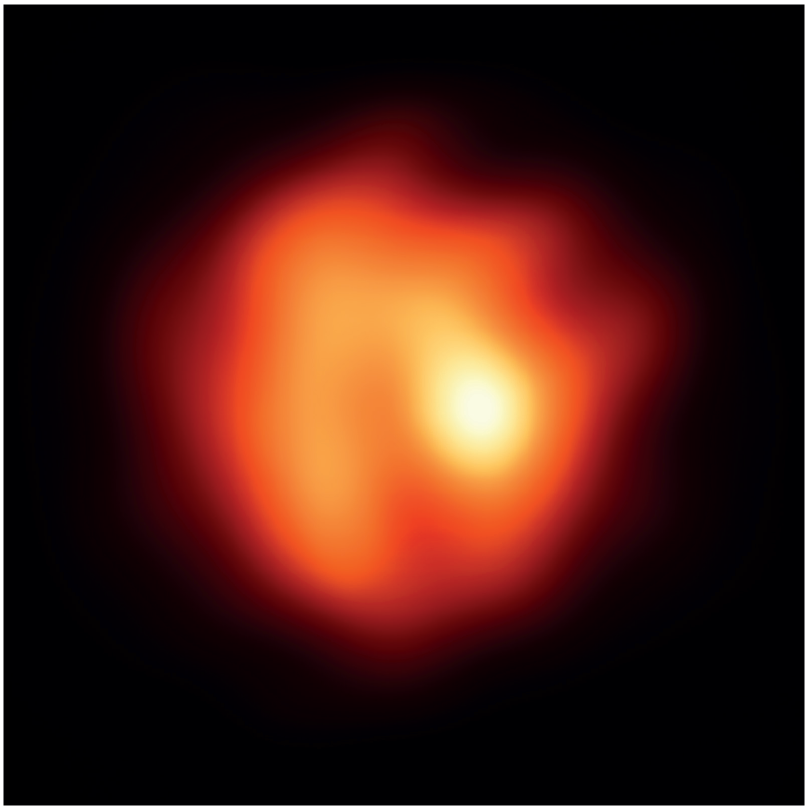
NETWORKING TELESCOPES

Astronomers can create a 'virtual' telescope on Earth using a process called interferometry. By arranging several telescopes (collectively known as an array) into a particular physical configuration, it is possible to gather the electromagnetic signals collected by each from the target object and combine them to build up a final image. The separation between each telescope is called the baseline, and the more baselines astronomers use as the Earth rotates over the course of a night, the higher the resolution of light that they can collect from the object under scrutiny.

This innovative technique was used in 2007 to acquire the first ever image of the surface of a Sun-like star, namely Altair in the constellation Aquila (see *All in a spin*, *AN*, January 2018), by astronomers at Georgia State University's Centre for High Angular Resolution Astronomy (CHARA).

The CHARA telescope array, located on Mount Wilson in California, comprises half-a-dozen one-metre telescopes. It can observe detail equivalent to looking at a penny 16,000 kilometres (10,000 miles) away, making it one of the most powerful interferometers currently in operation. John Monnier of the University of Michigan, USA, led an international team that observed Altair using four of the six telescopes within the array.

"Imaging the surface of Altair for the first time immediately showed us new things," says Monnier. "We were able to prove the existence of gravity darkening, which is an effect where the rapid rotation of the star makes the poles appear brighter than the equator, and we showed that it didn't match our best theory. We could also see the incredible importance of rotation on massive stars, something that was previously poorly understood since we can't study these effects on our slowly rotating Sun."

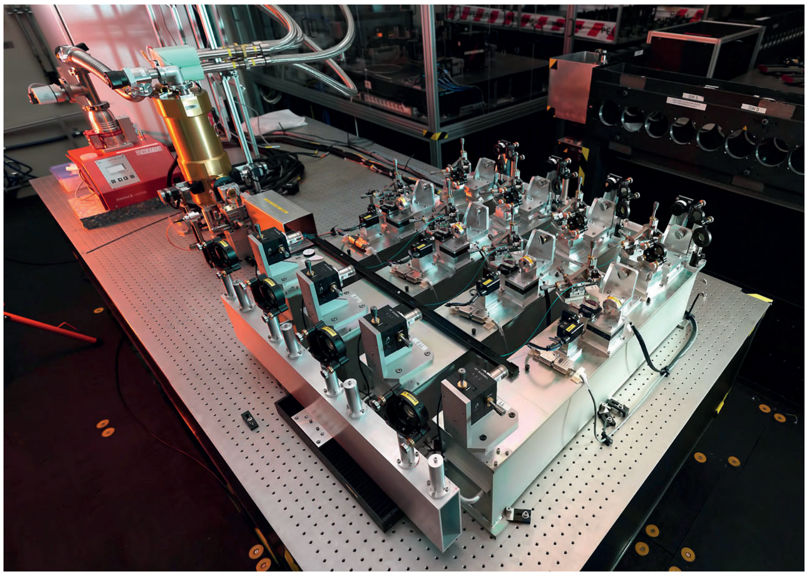


▲ Very Large Telescope Interferometer image of the red giant star R Sculptoris, showing it shedding its outer layers as it slowly turns into a planetary nebula. Image: ESO/M. Wittkowski.

SPOTTY STARS

In 2011 the MIRC (Michigan InfraRed Combiner) instrument, used to combine the light from each of CHARA's telescopes, was upgraded so that it could use all six telescopes in unison. With more telescopes came the ability to observe finer detail.

Rachael Roettenbacher, a postdoctoral researcher at Stockholm University in Sweden, has been working with a fully functioning MIRC to observe 'starspots' created by the presence of a strong magnetic field on the surface of distant giant stars. "We observe the stars through one full stellar rotation, which typically takes one to three weeks," she says.



▼ The PIONIER instrument, which combines the light from the Very Large Telescope Interferometer to observe the surface of stars. Image: ESO.

The rotational motion of the star spinning on its axis combined with the movement of an electrically conductive hot plasma within its interior creates a dynamo effect that generates magnetic fields deep within the star. Starspots are dark, cool patches that represent areas of concentrated magnetic activity that have broken through to the surface. They are temporary features that can last anywhere from a few hours to several months, and the more starspots there are, the more magnetically active the star is – they have been known to cover more than half of the surface of some stars.

Mapping the starspots, which are proxies for magnetic fields, gives astronomers the opportunity to test models of our own Sun's dynamo processes, as well as developing ideas of how it differs with varying levels of magnetic activity. "If the magnetic field is observed over time, that can give us insight into the dynamo's evolution and how that affects the star," says Roettenbacher.

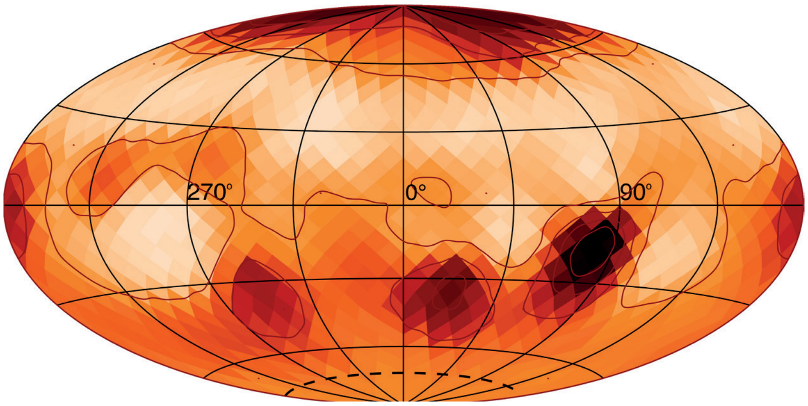
Her research has revealed three things about these giant stars. First is evidence that their starspots don't display the same northern/southern hemispheric symmetry as sunspots do on the Sun. Second is that magnetic fields emanate from across the whole surface of these stars, instead of being a more localised phenomenon, and third is confirmation that starspots can exist at the stars' poles, unlike on the Sun.

"The big results of our work have really shown off the detail that interferometry is presently capable of providing, while highlighting that active stars – in this case, those showing evidence of stellar magnetism through starspots – can be quite different to our Sun," says Roettenbacher.

POLARISED FINGERPRINTS

Another way to peek at a stellar surface is through a technique called polarimetry. This measures how light vibrates relative to its direction of travel. If surface features are present, then the starlight vibrates preferentially in one direction (it is 'polarised'), revealing itself through distortions in the star's spectrum – its unique electromagnetic 'fingerprint'. Therefore, by measuring how much the light is polarised, it is possible to map the surface features.

"Unlike both direct imaging and interferometry, the resolution acquired by polarimetry does not depend on the size of the telescope, [which is] a big advantage," explains Arturo López Ariste of the IRAP institute, part of University of Toulouse in France. "Another great advantage is that since we see our signal in perfectly identified spectra, we know exactly what we are looking at and its location."



▲ A map of starspots on the giant star zeta Andromedae. Image: Rachael Roettenbacher.

Using this technique, López Ariste and his colleagues have been able to image the surface of another well-known member of the night sky – Orion's red supergiant Betelgeuse, which is an enormous, pulsating star, about 1.6 billion kilometres across. Because Betelgeuse is so large, not only does it subtend a relatively large angular diameter on the sky (approximately 0.055 arcseconds), but its surface features are also correspondingly large.

"With Betelgeuse we know we are seeing bubbles of convection called 'granules', and we can measure their size and see them evolve over time," says López Ariste. "Recently we have also measured magnetic fields in the colder regions between granules. Our next step will be to build up a more complete picture of where these fields lie."

PIONEERING OBSERVATIONS

The European Southern Observatory (ESO) in Chile is home to the Very Large Telescope Interferometer (VLTI). Similar to the CHARA Array, the iconic four large 8.2-metre telescopes can be used in combination with a quartet of smaller 1.8-metre auxiliary telescopes to create several baselines.

Using the VLTI instrument PIONIER (the Precision Integrated-Optics Near-infrared Imaging ExpeRiment), a team of astronomers have recently succeeded in directly imaging granules on the surface of another star for the very first time, in one of the highest-resolution images of a star to date. Located 530 light years from Earth, pi-1 Gruis is a red giant star some 350 times larger and several thousand times brighter than our Sun.

ESO's Claudia Paladini led the PIONIER study, and she likens the granules to bubbles generated by water boiling in a pot. "Convection is one of the mechanisms used by nature to transport energy," she says. The granules are the top of convective cells, which are pockets of warm plasma moving upwards from deep inside a star, like a bubble rising to the top. Studying the granules gives clues about the processes that transport energy inside stars.

Granules on the Sun have been measured to be around 1,500 kilometres across, but the PIONIER observations have shown that those on pi-1 Gruis are huge, around 120 million kilometres in diameter. The difference in size is a result of pi-1 Gruis having expanded outwards in all directions (similar to an inflating balloon) as it evolved into a red giant. When our Sun also becomes a red giant, its granular cells will also stretch out like those seen on pi-1 Gruis.

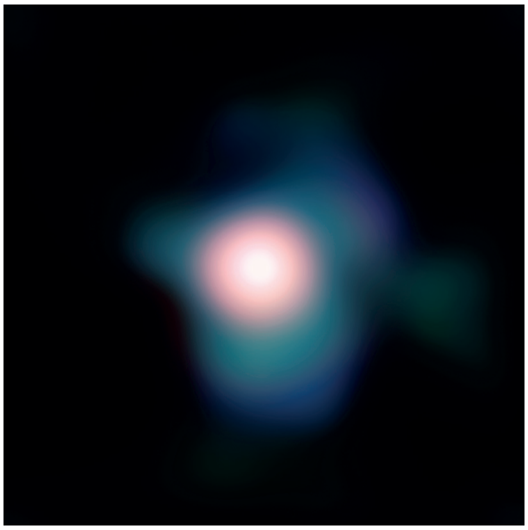
"For many years, direct observations of granulation were only possible for the Sun," says Paladini. "We can now directly see these structures on other stars 'by eye', thanks to interferometry, and it is much easier to check whether we correctly understand the physics involved."

The ability to image the surfaces of distant stars has progressed rapidly over the past 15 years, allowing astronomers to see things that seemed almost impossible to image before.

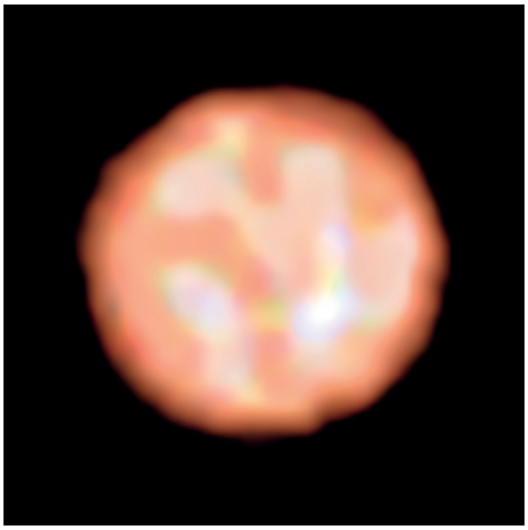
"Humans have been wondering about these same points of light in the night sky for more than 10,000 years," says Monnier. "It's thrilling to now be able to make stunning images and see them in detail."

Paladini points out that by studying other stars, we can begin to understand what is happening closer to home. "A few billion years ago, pi-1 Gruis system probably looked similar to what our Solar System does today," she says. "By using the VLTI, we are able to take a look into our future by imaging something that happened in the past."

Dr Amy Tyndall has a PhD in astrophysics and is an Edinburgh-based science communicator.



▲ The red supergiant Betelgeuse, as seen by the Very Large Telescope Interferometer. Image: ESO/P. Kervella.



▲ The PIONIER instrument on the Very Large Telescope Interferometer has imaged granulation of the red giant star pi-1 Gruis. Image: ESO.