AstroTalk: Behind the news headlines of January 2017

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Pulsars—enigmatic objects that remain as mysterious as when they were first discovered...

When a star with a birth mass of at least 20 times that of our Sun eventually explodes as a supernova, its remaining core of about 500,000 Earth masses is compressed to a size of only about 30 kilometres while it collapses into a so-called 'neutron star.'

Neutron stars rotate rapidly, which is simply a consequence of one of the fundamental laws of Nature, that of the *conservation of angular momentum*. Because of the collapse of the massive progenitor star into a very small volume, the rotation rate of the core needs to increase significantly to maintain the total angular momentum in the system. After all, the system's total energy must go somewhere, so it is redistributed in the form of rotational energy.

This rapid rotation causes charged particles to stream out from the magnetic poles – mostly in the form of radio or X-ray emission, although optical and/or gamma-ray emission has also been reported – along the spinning neutron star's magnetic axis. The latter is not necessarily aligned with the object's rotation axis, which therefore causes the appearance of a pulsed beam, hence the name 'pulsating star' or pulsar.

Like cosmic lighthouses sweeping the Universe with bursts of energy, pulsars have fascinated and baffled astronomers since they were first discovered 50 years ago. Despite the discovery of the first pulsar as long ago as 1967, they remain mysterious objects until today, still revealing surprising new discoveries from time to time.

In fact, a new discovery published this month has upended the widely held view that all pulsars are among the most orderly ticking clocks of the Universe. A survey done at the Arecibo Observatory in Puerto Rico has fortuitously discovered two extremely strange pulsars that undergo a 'cosmic vanishing act.' Sometimes they are there, and then for very long periods of time, they are not.

Recognizing the existence of this strange behaviour was fortuitous in itself. It took great patience on the part of a team of radio astronomers at Jodrell Bank Observatory in the UK, led by Professor Andrew Lyne of the University of Manchester, to confirm the existence of these mostly invisible pulsars.

Intermittent pulsars are a rarely observed population of pulsars, which have two states—one when they pulse like normal pulsars (the ON state), and another when they mysteriously fail to work, producing no radio waves at all (the OFF state).

> "*They switch instantaneously between the states*," notes Lyne. "*They're ON and then they're gone, disappearing without any apparent warning*."

A 34-member pulsar study team used the seven-beam receiver of the Arecibo Observatory to conduct routine pulsar searches in what they call the Pulsar Arecibo L-Band Feed Array (or PALFA) Survey. The two recently discovered intermittent pulsars spend most of their time in the OFF state. Three other similar pulsars are also known, but they are mostly ON.

In September 2012, one of these new objects was discovered to emit very bright pulses, and it was labeled PSR J1929+1357. Of 169 new pulsars, follow-up observations of half of those had been initiated at Jodrell Bank Observatory, and this candidate was confirmed as a pulsar in February 2013 using the Observatory's 250-foot Lovell Telescope at the second attempt.

> "*During the next 9 months it was observed no fewer than 650 times—for 100 hours in total*," said Professor Benjamin Stappers of the Jodrell Bank Centre for Astrophysics and a co-author on the new publication. "*It was ON on only five occasions—just 0.8% of the time*."

The most important implication of this discovery is that there must exist an extremely large number of these 'vanishing act' pulsars. The PALFA survey, which is aimed at a section of the Milky Way visible to Arecibo's radio dish, only covers each position in the survey once. It probably passed over 130 similar pulsars, but this was the only one that was ON at the time of the observation.

In addition, if it were not for the early signals detected at Jodrell Bank Observatory, this pulsar could easily have been discarded as a false detection, likely arising from so-called 'radio-frequency interference.' The PALFA team estimates that there are about 3,000 such intermittent pulsars in the survey area, far more than the population of normal pulsars.

> "*These disappearing pulsars may far outnumber normal pulsars*," said Victoria Kaspi of McGill University in Canada and the principal investigator of the PALFA project. "*In fact, they may redefine what we think of as normal*."

Why this odd behaviour? After all, since the original pulsar discovery, they have been referred to as marvelously accurate cosmic clocks that tick steadily for millions years with a regularity that surpasses the ticking of our best laboratory clocks. But these long-term intermittent pulsars are mostly invisible, which is about as useful as having the clock on the wall that is hidden behind a curtain for most of the time.

> "*The explanation of the ON–OFF behaviour remains a puzzle*," says Seymour. "*It indicates that the pulsar environment is changing, but just what those changes entail is open to debate.*"

A property of 'normal' pulsars is that their pulse rate slows very gradually over time. However, recent observations of these odd pulsars suggest that their rotational slow-down rate when OFF is only 80% of the rate when ON. The PALFA team suspects that the stream of charged particles, which drive the radio beams emanating from the pulsar, also causes the pulsar to spin down more rapidly.

When OFF, this particle stream fails for some reason and the spin-down rate is reduced. But, as Seymour notes, there is as yet no agreement in the pulsar community as to the ON–OFF mechanism. The changing spin rate is inferred by calculating how many beats were missed during the pulsar's invisible phases.

PALFA surveys are ongoing, and no one can predict if and when more examples of this fascinating new phenomenon will be found. Catching another intermittent pulsar in its ON mode is up to chance. Is there another candidate out there ready to reveal its secrets, or will it forever lurk hidden in the dark unknowns of space? Lyne hopes that follow-up measurements of PSR J1929+1357 will provide a rare insight into the physics of the pulsar emission mechanism and the changing spin-down phenomenon.

Two other studies published this month also focus on the intriguing nature of radio and X-ray pulsars. International teams of astronomers suggest that recent images from NASA's *Chandra X-ray Observatory* of two pulsars—Geminga and B0355+54—may help shine a light on the distinctive emission signatures of pulsars, as well as their often perplexing geometry.

Interestingly, the pulsar beams rarely match up across the wavelength range, said Bettina Posselt from Penn State University (USA). The shapes of observed radio and gamma-ray pulses are often quite different and some of the objects show only one type of pulse or the other. These differences have generated debate about the pulsar model.

"*It's not fully understood why there are variations between different pulsars*," said Posselt. "*One of the main ideas here is that pulse differences have a lot to do with geometry—and it also depends on how the pulsar's spin and magnetic axes are oriented with respect to line of sight whether you see certain pulsars or not, as well as how you see them*."

Chandra's images are giving the astronomers a closer-than-ever look at the distinctive geometry of the charged particle winds radiating in X-rays and other wavelengths from the objects, according to Posselt. Pulsar wind nebulae (PWN) are produced when the energetic particles streaming from pulsars shoot along the stars' magnetic fields, form tori—doughnut-shaped rings—around the pulsar's equatorial plane, and jet along the spin axis, often sweeping back into long tails as the pulsars travel at speeds of up to hundreds of kilometres per second through the interstellar medium.

> "*This is one of the nicest results of our larger study of pulsar wind nebulae*," said Roger Romani, professor of physics at Stanford University (USA) and principal investigator of the *Chandra* PWN project. "*By making the 3D*

structure of these winds visible, we have shown how one can trace back to the plasma injected by the pulsar at the centre. Chandra's fantastic X-ray acuity was essential for this study, so we are happy that it was possible to get the deep exposures that made these faint structures visible."

A spectacular PWN is seen around the Geminga pulsar. Geminga—one of the closest pulsars at only 800 light-years distance from Earth—has three unusual tails, said Posselt. The streams of particles spewing out of the poles of Geminga stretch out for more than half a light-year, more than 1,000 times the distance between the Sun and Pluto. Another, shorter tail also emanates from the pulsar.

The astronomers said that a very different PWN picture is seen in the X-ray image of another pulsar, B0355+54, which is located at about 3,300 light years from Earth. The tail of this pulsar has a cap of emission, followed by a narrow double tail that extends almost five light-years away from the star.

While Geminga shows pulses at gamma rays, but is radio-quiet, B0355+54 is one of the brightest radio pulsars, but fails to show gamma rays.

"*The tails seem to tell us why that is*," said Posselt, adding that the pulsars' spin and magnetic axis orientations influence what kind of emission is seen on Earth. Geminga may have magnetic poles quite close to the top and bottom of the object, and nearly aligned spin poles, much like Earth. One of the magnetic poles of B0355+54 could directly face the Earth. Because the radio emission occurs near the magnetic poles, the radio waves may point along the direction of the jets. Gamma-ray emission, on the other hand, is produced at higher altitudes in a larger region, allowing those pulses to sweep larger areas of the sky.

> "*For Geminga, we view the bright gamma-ray pulses and the edge of the pulsar wind nebula torus, but the radio beams near the jets point off to the sides and remain unseen*," Posselt said.

The strongly bent tails offer the astronomers clues to the geometry of the pulsar, which could be compared to either jet contrails soaring into space or to a bow shock similar to the shockwave created by a bullet as it is shot through the air.

Oleg Kargaltsev from George Washington University (USA), who worked on the B0355+54 study, said that the orientation of the object plays a role in how astronomers see the pulsar as well.

> "*For B0355+54, a jet points nearly at us so we detect the bright radio pulses while most of the gamma-ray emission is directed in the plane of the sky and misses the Earth*," he said. "*This implies that the pulsar's spin axis direction is close to our line-of-sight direction and that the pulsar is moving nearly perpendicularly to its spin axis*."

Noel Klingler, a graduate student at George Washington University and lead author of the B0355+54 paper, added that the angles between the three directions—the spin axis, the line-of-sight, and the velocity—are different for different pulsars, thus affecting the appearances of their nebulae.

> "*In particular, it may be tricky to detect a PWN from a pulsar moving close to the line-of-sight and having a small angle between the spin axis and our line-of-sight*," said Klingler.

In the bow-shock interpretation of the Geminga X-ray data, the pulsar's two long tails and their unusual spectrum may suggest that the particles are accelerated to nearly the speed of light through a process called Fermi acceleration. Fermi acceleration takes place at the intersection of a pulsar wind and the interstellar material, according to the researchers.

Although different interpretations remain possible for Geminga's geometry, Posselt said that *Chandra*'s images of the pulsar are helping astrophysicists use these objects as particle physics laboratories. Studying the objects gives astrophysicists a chance to investigate particle physics in conditions that would be impossible to replicate in a particle accelerator on Earth.

> "*In both scenarios, Geminga provides exciting new constraints on the acceleration physics in pulsar wind nebulae and their interaction with the surrounding interstellar matter*," she said.

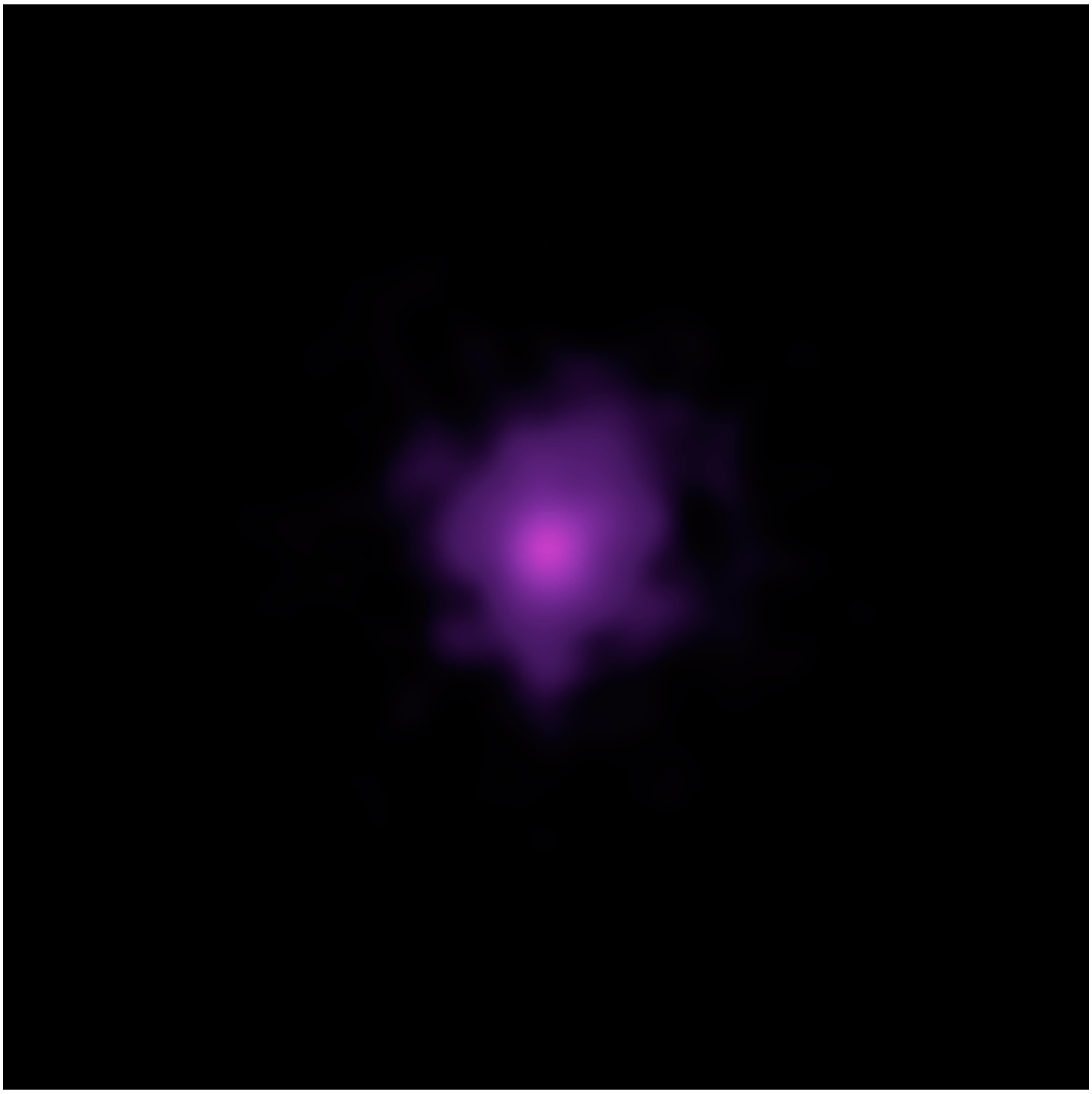

Figure 1: The pulsar pictured here, which resides in the galaxy Messier 82, 12 million light-years away, sends out X-ray beams that pass Earth every 1.37 seconds. Scientists studying this object with *NuSTAR* originally thought it was a massive black hole, but its X-ray pulse revealed its true pulsar identity. (*Credit: NASA/JPL-Caltech*)

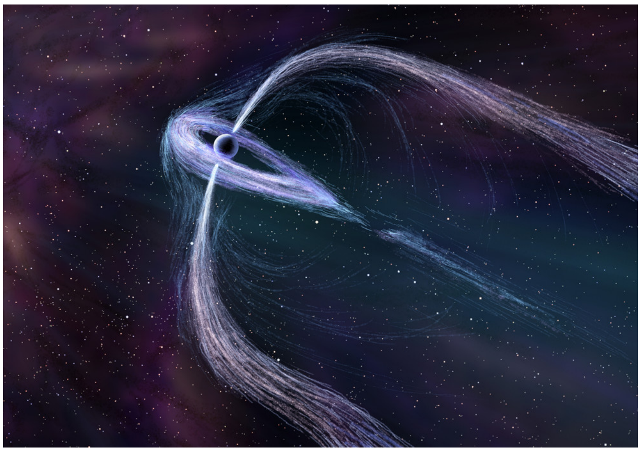

Figure 2: Artist's representation of what the three unusual tails of the Geminga pulsar may look like close-up. (*Credit: Nahks Tr'Ehnl*)

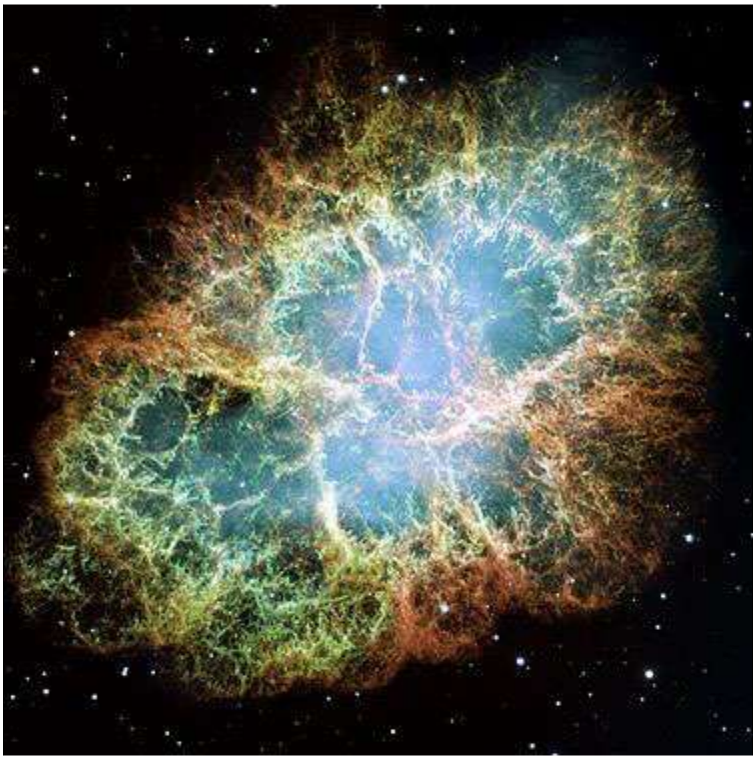

Figure 3: The Crab Nebula seen in the optical by the *Hubble Space Telescope*. The Crab is an example of a pulsar wind nebula. (*Credit: NASA/ESA-Hubble Space Telescope*)

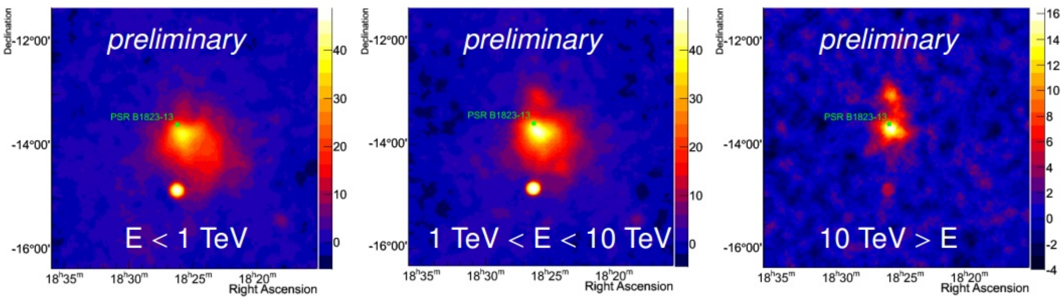

Figure 4: Significance maps of the pulsar wind nebula HESS J1825-137 region in three different energy bands. The size of the sources is clearly much reduced at high energies. Other sources within the field of view include the binary system LS 5039 and the hard spectrum source HESS J1826–130. (*Credit: Mitchell et al., 2016*)

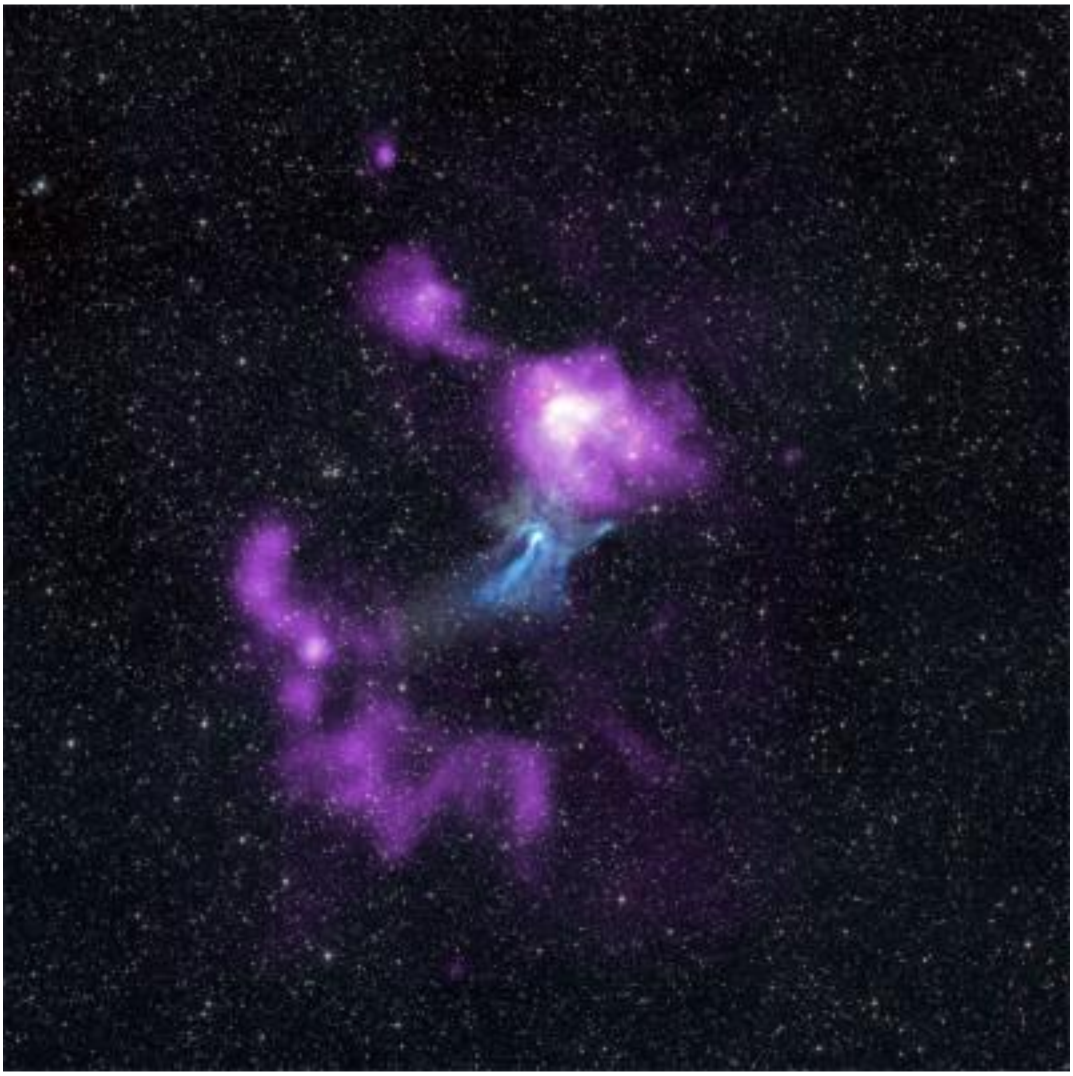

Figure 5: This image contains infrared, X-ray, and radio data of the pulsar known as PSR B1509-58. It shows the environment into which the pulsar's nebula is expanding. (*Credit: X-ray: NASA/CXC/SAO/P. Slane et al; Infrared: 2MASS/UMass/IPAC-Caltech; Radio: Molonglo Observatory Synthesis Telescope*)

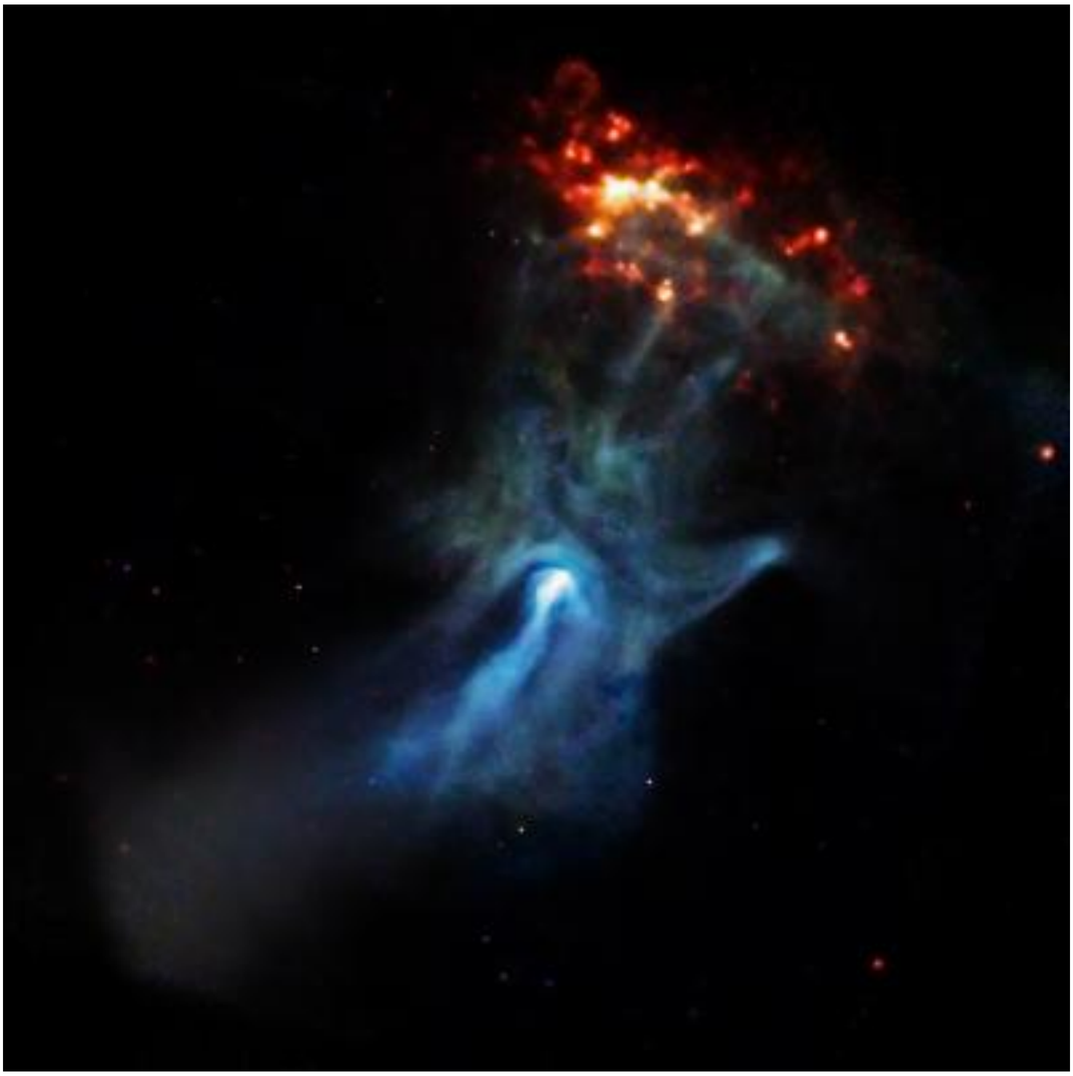

Figure 6: At the centre of this *Chandra* image, a pulsar – only 20 km in diameter – is responsible for this X-ray nebula that spans 150 light-years. This pulsar is spinning around almost seven times a second and has a magnetic field at its surface estimated to be 15 trillion times stronger than the Earth's magnetic field. This combination of rapid rotation and ultra-strong magnetic field drives an energetic wind of electrons and ions, ultimately creating the elaborate nebula seen by *Chandra*. (*Credit: NASA/CXC/SAO/P. Slane et al.*)

Figure 7: In this March 26, 2003, file photo, the world's second-largest radio telescope is seen from the air, at the Arecibo Observatory, in Puerto Rico. (*Credit: AP Photo/Tomas van Houtryve*)