Astronomy

Magnetic field lights up a stellar graveyard

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An X-ray imaging mission has unveiled the magnetic field in the environment of a dead star. The order and symmetry of the field will reshape our understanding of how it accelerates particles to ultra-high energies. See p.658

When massive stars die in dramatic supernovae, the beautiful stellar debris lingers in space for tens of thousands of years. The core of the dead star becomes a pulsar — a rapidly rotating, highly magnetized pulsating star the size of a city, which spews out a wind of fast-moving, electrically charged particles. This pulsar wind carries a strong magnetic field, typically shaped like a doughnut, that generates a gas cloud called a pulsar wind nebula as it slams into the surrounding material, accelerating the particles to energies much higher than can be achieved on Earth. On page 658, Xie et al. report imaging of the magnetic field in the acceleration zone of the Vela pulsar wind nebula, revealing a surprisingly highly ordered and symmetrical structure. This could help to shed light on why these nebulae are among the most powerful particle accelerators in the Universe.

Astronomers have been exploring pulsars ever since their discovery 55 years ago. In the past two decades, NASA’s Chandra X-ray Observatory has enabled close-up views of their nebulae, but direct imaging of the magnetic fields responsible for their high-energy radiation has not been possible. This is largely because magnetic fields are invisible — to visualize them, astronomers use the properties of light emitted when particles are accelerated, which occurs through a process known as synchrotron emission.

This type of radiation is generated when magnetic fields bend the paths of particles that are relativistic (meaning they are travelling at speeds close to that of light), and it can be emitted with wavelengths ranging from radio waves to X-rays. The electromagnetic field of the photons emitted by synchrotron radiation is expected to vibrate in one direction, which is perpendicular to that of the nebula’s magnetic field. So, measuring the direction of this vibration — the ‘polarization’ of the emission — can reveal which way the magnetic field is pointing (see go.nature.com/3ykafb7).

The onset of a pulsar wind nebula is referred to as the termination shock, and it resembles an arc of X-rays, which typically appears a short distance away from the pulsar (Fig. 1). Astronomers think that the particle energies get boosted precisely at the termination shock, although the mechanism through which this occurs is a topic of intense debate. Imaging the magnetic field driving the acceleration is crucial for solving this puzzle.

Before the IXPE mission, the only X-ray polarization measurement was that of the Crab nebula, first reported in 1976 (ref. 6). This nebula is perhaps the most iconic cosmic object, the supernova of which was witnessed from Earth in the year 1054. The Vela nebula is much older than the Crab, but looks like its identical twin when viewed with Chandra’s sharp X-ray eyes. At a distance of around 300 parsecs away, Vela is also much closer to Earth than is the Crab, which makes it possible to obtain a close-up view. Vela formed when a massive star exploded sometime between 10,000 and 20,000 years ago, leaving behind a supernova remnant spanning around 16 full Moons across Earth’s sky.

![Figure 1](image-url)
The measured polarization varies slightly with energy and location, but it is high across the nebula, and higher than any previously reported X-ray polarization of a cosmic source, including that of Vela’s twin, Crab. This suggests that the Vela environment is more efficient at creating order than is Crab’s environment, providing X-ray emission that is not polluted by hot gas or turbulent flows. Equally stunning is the fact that this order is maintained on a scale beyond the compact nebula, extending out into the part of the radio nebula that houses particles that are older and less energetic than those near the pulsar. This is intriguing because the nebulae of middle-aged objects, such as Vela, are expected to have been crushed by a reverse shock that bounces back through the ejected layers of the star, introducing some disorder into the process. The curvature of the magnetic field in the outer nebula is consistent with this scenario, because it isn’t perfectly symmetrical.

A highly ordered magnetic field challenges models predicting that unstable flows or turbulence have key roles in accelerating particles in ultra-relativistic winds. By modelling the X-ray arcs and jets seen in both the Vela and the Crab nebulae, researchers have put forward theories suggesting that a substantial fraction of the magnetic energy in these nebulae must be stored in a turbulent or highly disordered component.

Xie et al. show that this is not the case for Vela, and suggest that other processes, such as relativistic reconnection—a process that breaks and reconnects magnetic fields in a relativistic plasma—could energize particles close to the termination shock. Turbulence is, however, supported by data from other supernova remnants that are younger than Vela. The IXPE measurement of the Vela nebula thus challenges models for particle acceleration that involve chaos, and suggests that some of the most advanced simulations of relativistic winds need to be revisited.

So, is turbulence more crucial than order in young objects, or order responsible for their older counterparts? Or is Vela’s environment unique? Unfortunately, the IXPE has an imaging resolution of approximately 30 arcseconds (the equivalent of half the width of a little finger), and this translates to around 0.04 parsecs for objects as distant as Vela. This is comparable to, or even larger than, the distance between Vela’s bright X-ray arcs, limiting our ability to study the role of turbulence on these scales. Turbulence could still be key to this process, but on scales or energies beyond the reach of the IXPE. Another consideration is the dynamic nature of the X-ray arcs and jets, and its impact on the level or direction of the X-ray polarization.

Vela seems like the perfect case study for visualizing magnetic fields up close in pulsar wind nebulae. Despite being middle-aged, Vela’s highly polarized X-ray light has unveiled the invisible field at its nebula’s core and in its acceleration zone. Xie and colleagues’ study therefore offers hope for the many other similar objects that make up the majority of accelerators in our Galaxy (see go.nature.com/3bd92nd). Will these objects fall into the category seemingly established by Vela, or will there be a zoo of magnetic-field geometries and particle-acceleration mechanisms at play? Only time will tell, but one thing is certain: the IXPE has ushered in a new era of X-ray polarization imaging.