A Rare Pulsar Largely Eclipsed by Its Nearby Companion

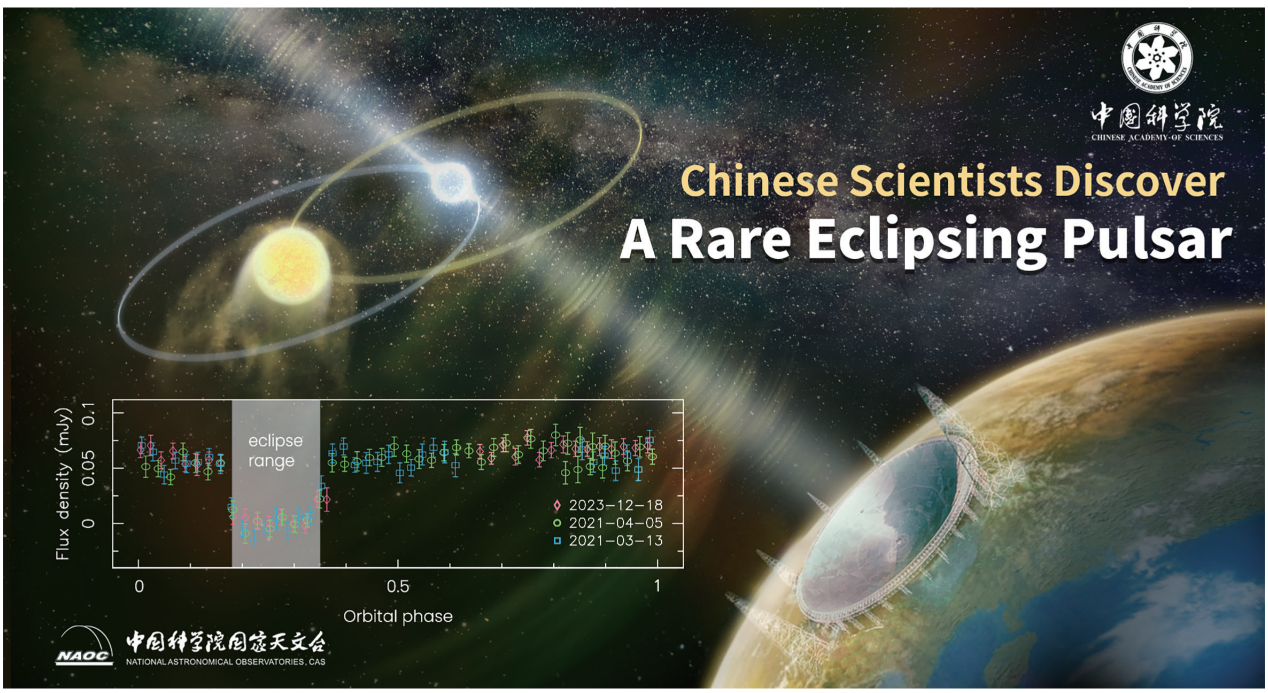
By SONG Jianlan

A group of Chinese astronomers detected a weird pulsar that keeps emitting radio beams in long, regular pauses. After years of follow-up observations and careful data analyses, they finally revealed this exotic pulsar in *Science* on May 23 as a rare case: it turns out to be eclipsed by a companion, very likely a helium star, with a mass similar to the Sun and in an orbit smaller than the solar radius.

This scene is interpreted as the immediate result from an ephemeral stage predicted by theorists for binary pulsar evolution that had never detected before: the pulsar stays within the outer layer of its companion, hence sharing a common envelope (CE) with the latter, and then strips off the envelope in one thousand years, a very short while compared to the binary's long evolution.

According to the simulation by the team members from Nanjing University, nowadays there are only 16 to 84 such binary systems in the vast Milky Way; moreover, not all of them are detectable. The pulsars' narrow

Using FAST, the Five-hundred-meter Aperture Spherical radio Telescope, a team of scientists led by Prof. HAN Jinlin from the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) detected an unusual millisecond pulsar whose radio emission is blocked by its nearby companion the long eclipse lasts for one sixth of their common orbital cycle. Such a binary system is interpreted as the result from a short phase of binary evolution that had never been detected. (Image: Produced by Bureau of International Cooperation, Chinese Academy of Sciences)



beams might fall off our line of sight, or their location might be too far away to allow their radiation to reach the Earth before dying out.

With the valuable observational data from this rare binary case, the scientists not only strictly constrain the companion as a new type of companion star for pulsar binaries, but also reconstructed the milestone scenarios of such binaries' evolution back to about 100 million years ago, and inferred how it will look like in around 10 million years. The research is acclaimed as offering insights into stellar evolution as well as accretion physics of compact objects, and might inspire prediction of merging compact binaries as potential sources of gravitational waves.

A Rare Scene

Years ago, using FAST, the Five-hundred-meter Aperture Spherical radio Telescope of China, a team led by Prof. HAN Jinlin from the National Astronomical Observatories, Chinese Academy of Sciences (NAOC) detected an unusual millisecond pulsar in a survey of the Milky Way. The pulsar spins about one hundred times per second. After a few measurements, they found that the pulsar period is variable, indicating that it is orbiting around a shared center of mass with an invisible companion star every 3.6 hours. Unlike normal pulsars, this pulsar's signals disappeared for about one-sixth of the orbital period. The team reckoned that such periodical emission pauses are resulting from eclipses by its companion.

Pulsars, highly magnetized and rapidly spinning neutron stars, have fascinated astronomers since they were first discovered in 1967 by Jocelyn Bell Burnell and Antony Hewish. They keep emitting beams of electromagnetic radiation from their magnetic poles, and only when such beams sweep across the Earth, can we detect them with radio telescopes — as regular and short radio pulses. That is why we call them pulsars. About them, many mysteries are still pending for answer, among which is their evolution, especially for binary pulsars. Concerning their evolution, lots of details are yet to understand: how the two objects interact and co-evolve in a binary system, how their orbital separation shrinks sharply, how they exchange their matter, how the neutron star accretes nearby matter and gets recycled to a high spinning rate with a period of milliseconds, and how the compact star blows away the hydrogen layer of the companion ... all are baffling scientists.

Existing theoretical models predict that in such binary systems, the more massive one generally evolves faster, and once running out of fuel for the fusion in its core, it will collapse into a compact star, like a neutron star or a black hole. The lighter one, continuing on its evolution, would fall a prey of the compact star's mighty gravity, with its matter being sucked up by the latter. While the mass loss goes on, the prey would expand, growing to a size even big enough to contain both itself and the predator — to form a CE.

This CE might be ejected rapidly, sustaining for only about one thousand years — just an instant moment compared to the binary's long evolution lasting for hundreds of million years. The compact star, fed by its companion, would spin up by the obtained mass and energy. Meanwhile it will blow away the hydrogen layer from the CE, leaving the companion with a stripped helium core.

Therefore, the existence of a helium star in the binary system means a lot. It can be interpreted as a residual from the CE stage. But before coming to this conclusion, the scientists need to allow for other possibilities. What else can cause the long, regular pauses in pulsar emission? What if it is not even a companion, but something else, say, the remnants from some compact objects?

Close-up Observation of the Binary Pulsar

It took the team some time to identify the cause of the emission gaps.

The astronomers spent four and a half years in follow-up observations using FAST, the most sensitive radio telescope in the world. They carefully measured the times of arrival (TOAs) of the pulsar's pulses. The interval between two arrivals equals to its spinning period, which is typically very stable for millisecond pulsars. Actually, millisecond pulsars generally spin so stably that they can be used to calibrate an atomic clock, or guide a spacecraft for interstellar navigation. This weird pulsar, registered as PSR J1928+1815, has a spinning period as short as 10.55 millisecond. Based on the careful measurements, the team fitted a model to calculate the parameters of the pulsar and its companion. They found out that the two orbit each other every 3.60 hours.

The team hence performed three long observations each covering the 3.6-hour orbital period of the overall binary system. They detected some regular long gaps in radio emission, covering about one sixth of the binary's orbital period. All such gaps occurred when the companion moves to the front of the pulsar, resulting in regular eclipses just like a solar eclipse.

Identifying the Companion

Not all companions can do this, however. What kind of an object can block the emission? The delay of TOAs in various orbital phases suggests that the orbital separation of the two objects in the binary system spans about 500,000 kilometers. What a star can eclipse the pulsar so significantly at such a small distance?

Thankfully the team have accumulated high-quality data to narrow down the possible candidates into an exclusive group using different parameters. Combining their observations with the massive data from the past observations on different pulsars accumulated over decades by the astronomical community, they can constrain the upper and lower mass thresholds of the companion star.

Complicated calculation showed that the mass of the invisible companion should be slightly more massive than the Sun — This directly excluded some types of ordinary stars and shortlisted the candidates.

This companion could be a massive white dwarf or a neutron star, if taking only its mass into consideration; however, neither of them can produce a stellar wind dense enough to block the radio emission of the pulsar for so long a time. Nor can it be a "main sequence" star (MS) — a gaseous star in the major stage of stellar evolution as the Sun, where the hydrogen atoms in its core are being fused into helium atoms. An MS with a mass comparable to the Sun would be of much larger a size than the whole binary's orbit, which is in conflict with the observation.

The team even considered the possibility of spider pulsars, which can also exhibit irregular eclipses in radio emission. However, in this case, the "companion" would either be an MS of much larger a size, or the remnant from either a brown dwarf or a white dwarf of much smaller a mass. Moreover, all the eclipses of PSR J1928+1815 are regular. Obviously, it is not a spider pulsar.

Combining the mass and the size of the potential companion, the team inferred that it could be a helium star: with much smaller a radius, it can produce a strong stellar wind to block out the emission for long enough a time, well matching the eclipses observed.

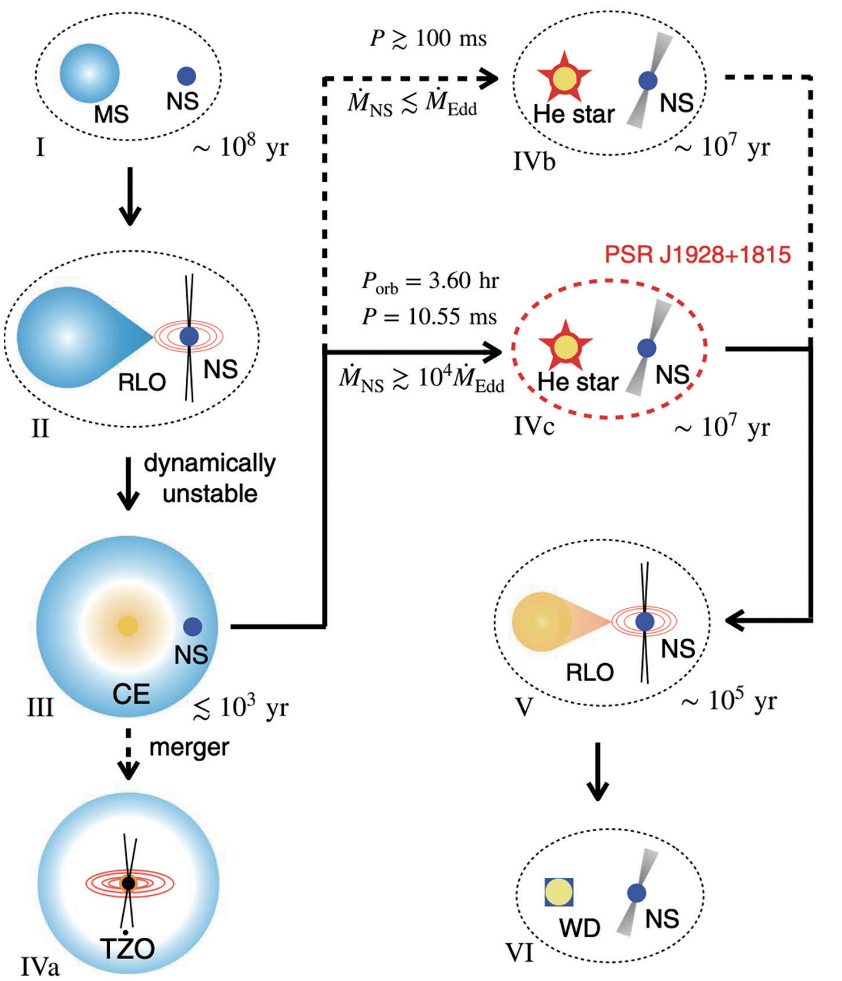
With a helium star as the companion, a "bow shock" of stellar wind can be produced within the binary. This shock could be the cause for the eclipses, interpreted the authors. Both the pulsar and the helium star keep shedding high-energy particles, just like the solar wind, and the stellar wind from the pulsar is stronger and overwhelming. Therefore, when the two collide, a shock of bow-shape is produced, enveloping the helium star. Such a sheath can absorb the emission from the pulsar at a certain frequency to eclipse the emission — again matching the occurring frequency of the observed pauses.

The team tried to search for the companion in other wavelengths, looking for counterparts from archived optical imaging and searching in optical, infrared, gamma and X-ray catalogs, but no potential counterpart of the object was found. The team attribute this to the companion's remote location of 30 thousand light-years away behind a spiral arm of the Milky Way, where the stellar dusts could absorb and scatter short-wave electromagnetic signals. This "failure," however, also conforms to how a helium star radiate in such wavelengths.

The Past and Future Lives of Such a Pulsar Binary

The companion, however, could have been an MS at the beginning, as shown in major scenarios of the binary's evolution reconstructed by the team. With data from this rare case resulting from a very special intermediate stage of stellar evolution, they were able to update the existing theories with great detail, fixing the potential trajectory for a binary pulsar's evolution.

About 100 million years ago, the team suggested, the more massive one of the two MSs in a binary system evolved into a neutron star (stage I). The left MS gradually ran out of hydrogen after long fusion in its core, and expanded to a huge size — so huge that its gravity failed to bound its gaseous matter in face with the neutron star's mighty gravity. At this point, the neutron star, much more massive than the MS and highly magnetized, began to sucked up the matter from the star (stage II). This accretion caused some dynamical instability in the orbital system, and led to further expansion of the star — now possibly a giant, and a CE hence is formed (stage III). The star's expanding envelope engulfs the compact star, causing both objects to orbit within a shared gaseous envelope. The compact star spirals in, and the orbit between the two largely shrunk to form a much tighter binary system. Strong friction occurs between the envelope and the dense



Scenarios of a binary pulsar's evolution: NAOC scientists reconstructed the possible evolution pathway along which the pulsar binary PSR J1928+1815 could have come from since about 100 million years ago, and will go in 10 million years and beyond. (Image: NAOC)

cores of the giant as well as the compact star, transferring orbital energy and angular momentum to the envelope. If enough energy is transferred, the envelope could be ejected, leaving behind an even tighter binary.

This stage might sustain about only 1,000 years, a very short while in the long evolution. After that, the binary will evolve in three possible directions, depending on the competition between the shrinking of the orbital separation and the evolution of their envelope.

If the two objects get closer rapidly, quicker than the speed their envelope ejects, the neutron star could merge with the core of the star to become an interesting celestial body named "Thorne-Żytkow Object," which would look like a red supergiant containing a neutron star at its core (stage IVa). If the envelope is ejected ahead of the merger, the pulsar would strip off the hydrogen from the CE, leaving behind a stripped helium core of the MS (stage IVb and IVc), with the subsequent pulsar spinning at different rates. In the case of PSR J1928+1815 (corresponding to stage IVc), the pulsar gets more momentum to spin up to become a millisecond pulsar.

The aging helium star might not be able to produce a supernova due to its modest mass, predicted the authors. As a result, it might further expand to a larger size, going too far to hold its own gaseous matter. Hence a new round of mass loss happens, feeding its compact neighbor (stage V). When the mass loss continues to a certain extent, it will collapse into a white dwarf, forming a renewed binary system with a recycled predator pulsar (stage VI).

For the case of PSR J1928+1815, the team estimated, to arrive at the pulsar' current spinning rate, it needs to take up at least a volume of mass equivalent to 1% of the Sun's. The team then calculated the maximum mass a neutron star can swallow during a period of one thousand years — the longest duration the envelope can survive — via the so-called Eddington accretion, a traditional model for accretion physics. They found that the total volume would fall much smaller than needed. To accumulate to this huge energy, the team hence proposed, the super-Eddington accretion is required, and neutrinos and photons are released to carry more energy. This could make an important example demonstrating neutrino heat dissipation mechanism.

This intriguing binary pulsar may offer more insights into details for binary evolution, with in-depth analysis going on.

Reference

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