Pulsating gamma rays from neutron star rotating 707 times a second

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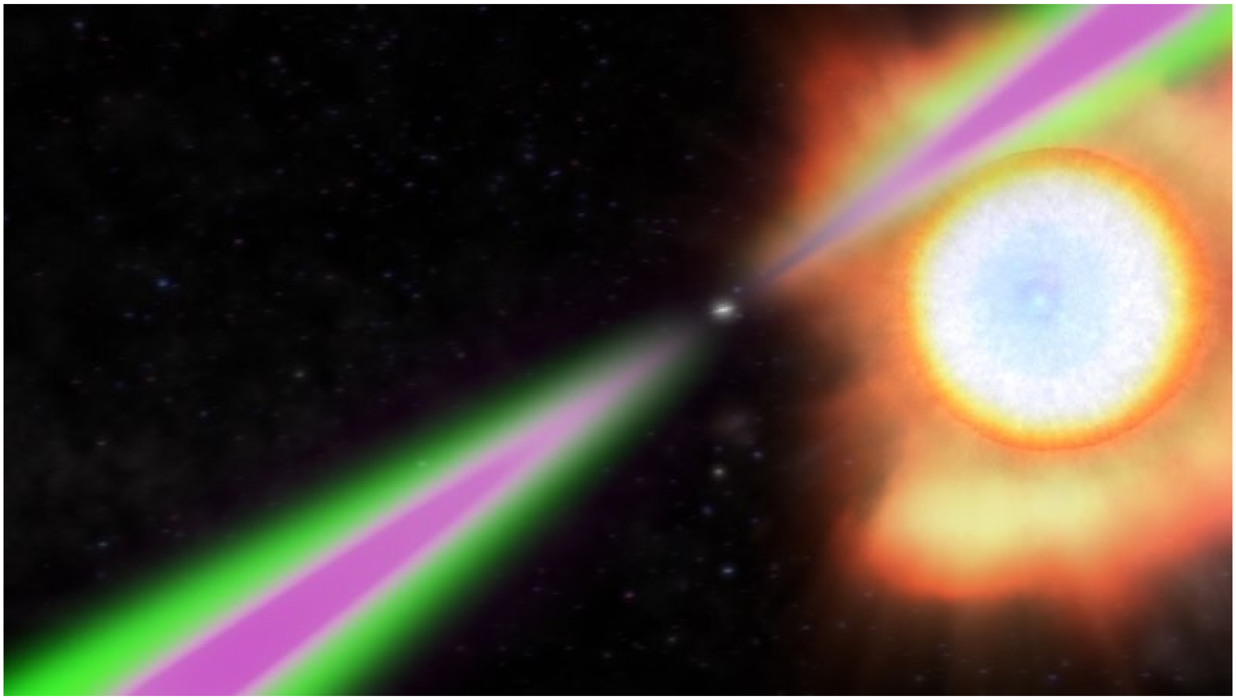


A black widow pulsar and its small stellar companion, viewed within their orbital plane. Powerful radiation and the pulsar's “wind” – an outflow of high-energy particles — strongly heat the facing side of the star to temperatures twice as hot as the sun's surface. The pulsar is gradually evaporating its partner, which fills the system with ionized gas and prevents astronomers from detecting the pulsar's radio beam most of the time. Credit: NASA's Goddard Space Flight Center/Cruz deWilde

An international research team led by the Max Planck Institute for Gravitational Physics (Albert Einstein Institute; AEI) in Hannover has discovered that the radio pulsar J0952-0607 also emits pulsed gamma radiation. J0952-0607 spins 707 times in one second and is second in the list of rapidly rotating neutron stars. By analyzing about 8.5 years worth of data from NASA's Fermi Gamma-ray Space Telescope, LOFAR radio observations from the past two years, observations from two large optical telescopes, and gravitational-wave data from the LIGO detectors, the team used a multi-messenger approach to study the binary system of the pulsar and its lightweight companion in detail. Their study published in the *Astrophysical Journal* shows that extreme pulsar systems are hiding in the Fermi catalogs and motivates further searches. Despite being very extensive, the analysis also raises new unanswered questions about this system.

Pulsars are the compact remnants of stellar explosions which have strong magnetic fields and are rapidly rotating. They emit radiation like a cosmic lighthouse and can be observable as radio pulsars and/or gamma-ray pulsars depending on their orientation towards Earth.

The fastest pulsar outside globular clusters

PSR J0952-0607 (the name denotes the position in the sky) was first discovered in 2017 by radio observations of a source identified by the Fermi Gamma-ray Space Telescope as possibly being a pulsar. No pulsations of the gamma rays in data from the Large Area Telescope (LAT) onboard Fermi had been detected. Observations with the radio telescope array LOFAR identified a pulsating radio source and—together with optical telescope observations—allowed to measure some properties of the pulsar. It is orbiting the common center of mass in 6.2 hours with a companion star that only weighs a fiftieth of our Sun. The pulsar rotates 707 times in a single second and is therefore the fastest spinning in our Galaxy outside the dense stellar environments of globular clusters.

Searching for extremely faint signals

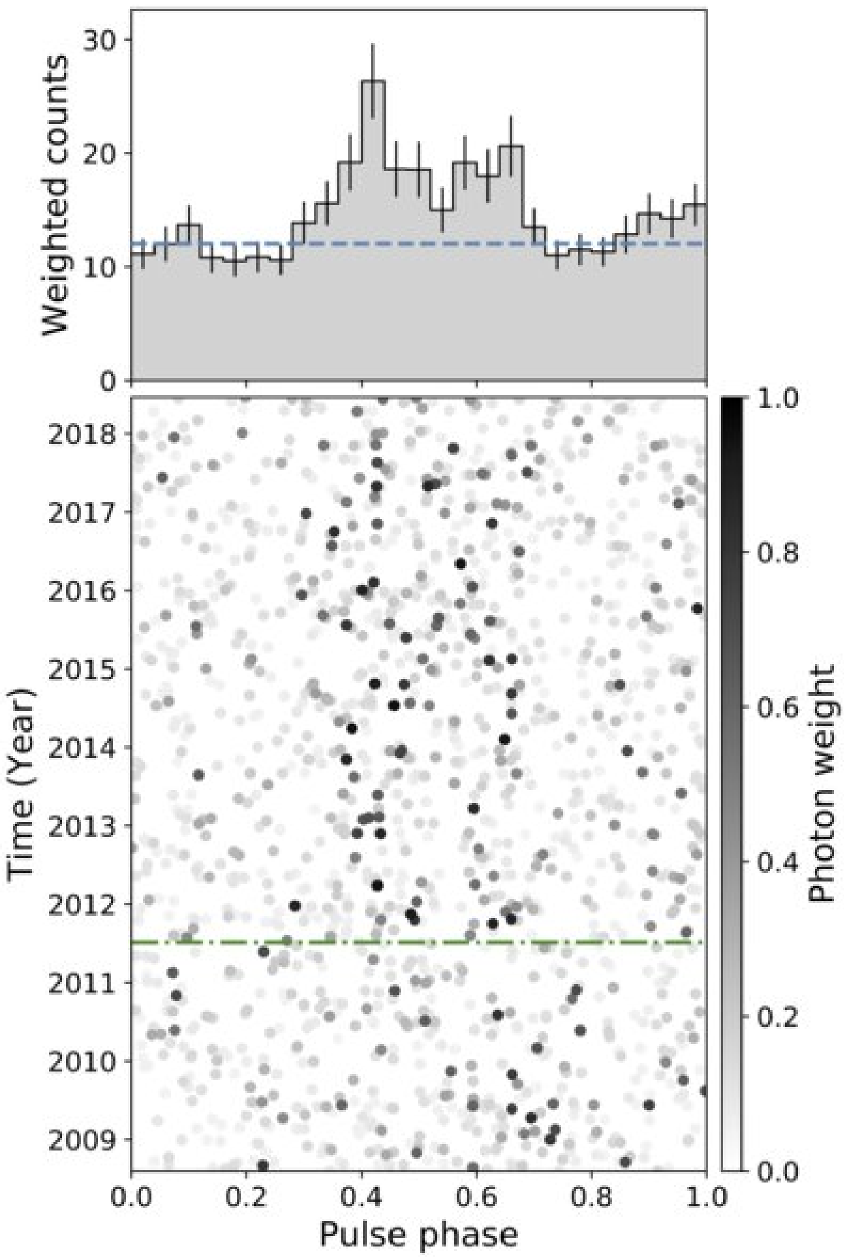
Using this prior information on the binary pulsar system, Lars Nieder, a Ph.D. student at the AEI Hannover, set out to see if the pulsar also emitted pulsed gamma rays. "This search is extremely challenging because the Fermi gamma-ray telescope only registered the equivalent of about 200 gamma rays from the faint pulsar over the 8.5 years of observations. During this time the pulsar itself rotated 220 billion times. In other words, only once in every billion rotations was a gamma ray observed!" explains Nieder. "For each of these gamma rays, the search must identify exactly when during each of the 1.4 millisecond rotations it was emitted."

This requires combing through the data with very fine resolution in order not to miss any possible signals. The computing power required is enormous. The very sensitive search for faint gamma-ray pulsations would have taken 24 years to complete on a single computer core. By using the Atlas computer cluster at the AEI Hannover it finished in just 2 days.

A strange first detection

"Our search found a signal, but something was wrong! The signal was very faint and not quite where it was supposed to be. The reason: our detection of gamma rays from J0952-0607 had revealed a position error in the initial optical-telescope observations which we used to target our analysis. Our discovery of the gamma-ray pulsations revealed this error," explains Nieder. "This mistake was corrected in the publication reporting the radio pulsar discovery. A new and extended gamma-ray search made a rather faint—but statistically significant—gamma-ray pulsar discovery at the corrected position."

Having discovered and confirmed the existence of pulsed gamma radiation from the pulsar, the team went back to the Fermi data and used the full 8.5 years from August 2008 until January 2017 to determine physical parameters of the pulsar and its binary system. Since the gamma radiation from J0952-0607 was so faint, they had to enhance their analysis method developed previously to correctly include all unknowns.



The pulse profile (distribution of gamma-ray photons during one rotation of the pulsar) of J0952-0607 is shown at the top. Below is the corresponding distribution of the individual photons over the ten years of observations. The greyscale shows the probability (photon weights) for individual photons to originate from the pulsar. From mid 2011 on, the photons line up along tracks corresponding to the pulse profile. This shows the detection of gamma-ray pulsations, which is not possible before mid 2011. Credit: L. Nieder/Max Planck Institute for Gravitational Physics

Another surprise: no gamma-ray pulsations before July 2011

The derived solution contained another surprise, because it was impossible to detect gamma-ray pulsations from the pulsar in the data from before July 2011. The reason for why the pulsar only seems to show pulsations after that date is unknown. Variations in how much gamma rays it emitted might be one reason, but the pulsar is so faint that it was not possible to test this hypothesis with sufficient accuracy. Changes in the pulsar orbit seen in similar systems might also offer an explanation, but there was not even a hint in the data that this was happening.

Optical observations raise further questions

The team also used observations with the ESO's New Technology Telescope at La Silla and the Gran Telescopio Canarias on La Palma to examine the pulsar's companion star. It is most likely tidally locked to the pulsar like the Moon to the Earth so that one side always faces the pulsar and gets heated up by its radiation. While the companion orbits the binary system's center of mass its hot "day" side and cooler "night" side are visible from the Earth and the observed brightness and color vary.

These observations create another riddle. While the radio observations point to a distance of roughly 4,400 light-years to the pulsar, the optical observations imply a distance about three times larger. If the system was relatively close to Earth, it would feature a never-seen-before extremely compact high density companion, while larger distances are compatible with the densities of known similar pulsar companions. An explanation for this discrepancy might be the existence of shock waves in the wind of particles from the pulsar, which could lead to a different heating of the companion. More gamma-ray observations with Fermi LAT observations should help answer this question.

Searching for continuous gravitational waves

Another group of researchers at the AEI Hannover searched for continuous gravitational wave emission from the pulsar using LIGO data from the first (O1) and second (O2) observation run. Pulsars can emit gravitational waves when they have tiny hills or bumps. The search did not detect any gravitational waves, meaning that the pulsar's shape must be very close to a perfect sphere with the highest bumps less than a fraction of a millimeter.

Rapidly rotating neutron stars

Understanding rapidly spinning pulsars is important because they are probes of extreme physics. How fast neutron stars can spin before they break apart from centrifugal forces is unknown and depends on unknown nuclear physics. Millisecond pulsars like J0952-0607 are rotating so rapidly because they have been spun up by accreting matter from their companion. This process is thought to bury the pulsar's magnetic field. With the long-term gamma-ray observations, the research team showed that J0952-0607 has one of the ten lowest magnetic fields ever measured for a pulsar, consistent with expectations from theory.

"We will keep studying this system with gamma-ray, radio, and optical observatories since there are still unanswered questions about it. This discovery also shows once more that extreme pulsar systems are hiding in the Fermi LAT catalog," says Prof. Bruce Allen, Nieder's Ph.D. supervisor and Director at the AEI Hannover. "We are also employing our citizen science distributed computing project Einstein@Home to look for binary gamma-ray pulsar systems in other Fermi LAT sources and are confident to make more exciting discoveries in the future."

More information: L. Nieder et al. Detection and Timing of Gamma-Ray Pulsations from the 707 Hz Pulsar J0952−0607, *The Astrophysical Journal* (2019). DOI: 10.3847/1538-4357/ab357e

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