A neutron star that's a fast particle accelerator may lie at the heart of the Crab Nebula

The pulsar in the Crab Nebula may be one of the most studied examples of its …

by **Matthew Francis** - Feb 17 2012, 12:00am CET

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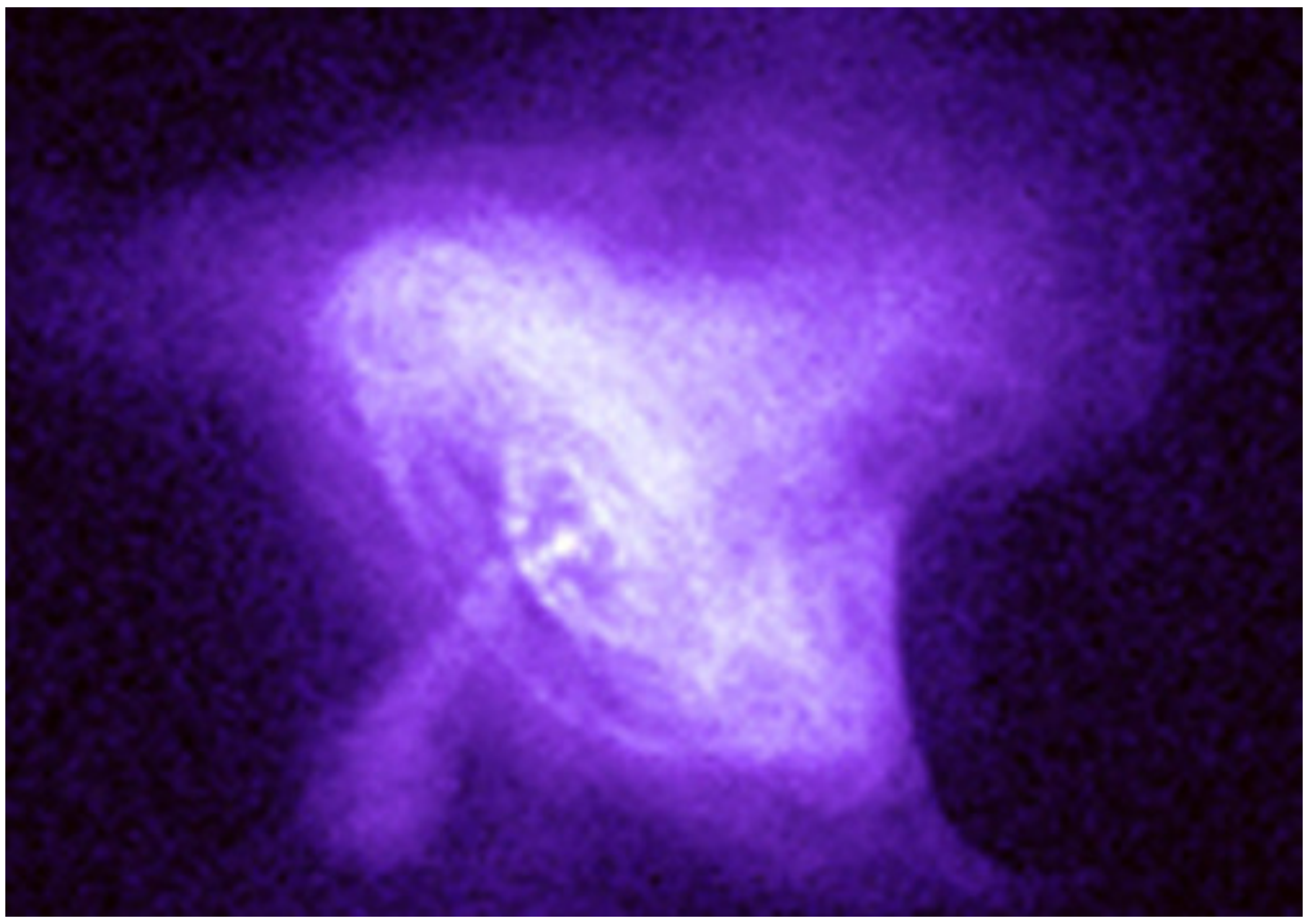

Chandra X-ray Telescope image of the central region of the Crab Nebula, showing the effects of the pulsar wind streaming out from the hidden central neutron star.

Photograph by chandra.harvard.edu

The Crab Nebula (also designated M1 or NGC 1952) is visible through small telescopes, which has allowed astronomers to observe its growth and evolution since the supernovae that created it became visible in 1054 CE. A pulsar was found in the center of the Crab in 1968. This rapidly rotating neutron star is the core of the star that went supernova to make the nebula. In the intervening decades, X-ray, gamma ray, and radio observations have mapped the region of the nebula closest to the pulsar. During that mapping, it became apparent that the Crab pulsar is one of the brightest sources of gamma rays observable from Earth.

Despite all of those observations, we still don't fully understand the Crab's precise gamma ray spectrum, particularly recently observed pulses of intense gamma radiation seen by the Fermi Gamma-ray Space Telescope. Existing models certainly do well at describing much of the complex interplay between the intense magnetic fields of the pulsar and the winds of charged particles flowing outward. But no single scheme seems sufficient to cover *all* the observed phenomena.

A potentially promising new model, proposed by F. A. Aharonian, S. V. Bogovalov, and D. Khangulyan, may fill in some of these blanks. It proposes that areas near the pulsar are acting as rapid particle accelerators, but don't boost electrons and heavier particles to the same extent.

Pulsars are exceedingly small despite their high mass: according to typical neutron star models, the Crab pulsar is approximately 30 kilometers in diameter, but contains nearly double the mass of our Sun. The intense gravitational influence and rapid rotation of pulsars place them firmly in the realm of relativity, while intense magnetic fields carry the enormous amounts of energy we typically encounter in particle accelerators.

In the region immediately surrounding the Crab pulsar, there is enough energy to produce pairs of electrons and positrons, which flow outward into the surrounding gas. This total flow is the *pulsar wind*, a plasma (an electrically neutral substance consisting of separate positive and negative charges) that moves very close to the speed of light.

Close to the pulsar, most of the energy in the pulsar wind is in the form of electromagnetic energy from the pulsar itself. Further out, the energy is mostly in the form of the kinetic energy of the fast-moving plasma particles. How this transition occurs is not completely clear; in particular, it's difficult to square with the 2011 observations of intensely energetic gamma ray pulses.

Though gradual acceleration of the plasma throughout the entire region of interest (a common explanation) is consistent with the behavior of the pulsar wind, gradual acceleration fails to explain the gamma ray signature, which spikes several orders of magnitude higher than the energy from emissions by the pulsar itself. The new model suggests that acceleration of the pulsar wind is rapid, and leaves electrons within the wind moving at roughly the same speed as heavier particles.

The electrons and positrons driving the pulsar wind are generated in the region around the *light cylinder* of the Crab pulsar. The energy present in the light cylinder of a pulsar comes from its intense electromagnetic fields, which carry away rotational energy from the neutron star.

The Aharonian-Bogovalov-Khangulyan model, published in *Nature* on February 15, argues that the electron-positron plasma cannot be moving very rapidly close to the pulsar, since too much of the energy there is electromagnetic. But the plasma's kinetic energy increases rapidly as it's accelerated away. The pulsar is emitting gamma rays, as mentioned previously; those photons collide with the electrons, transferring energy and momentum in a process known as inverse Compton scattering. This speeds up the wind. By the time the wind has reached a distance roughly 30 times the radius of the light cylinder, the energy balance shifts so that almost all of the energy is in the wind, with acceleration occurring very rapidly in a narrow region.

What's a light cylinder?

A light cylinder exists for anything that rotates. It contains the volume within a distance that relates the speed of rotation to the speed of light. At the edge of the light cylinder, an object would have to move at the speed of light to maintain an orbit that keeps it over the same location on the rotating body.

An analogy is useful: imagine a playground merry-go-round that goes around once every minute. If you run around the merry-go-round so that you also complete a circle in one minute, you could probably walk fast enough if you're five feet away. But you'd have to walk much faster for larger circles. If your circle is large enough, you'd have to run at the speed of light: that's the light cylinder for the merry-go-round.

Among the side effects of this acceleration is a spike in gamma ray emission, due to the fact that the wind is revolving around the pulsar as well as streaming outward. (Charged objects that curve through a magnetic field emit radiation to balance their energy books.) In this model, these emissions ensure that many of the electrons are moving at nearly the same speed as the protons within the plasma, which is not typical behavior: protons are much harder to accelerate due to their much larger mass.

If gradual rather than abrupt acceleration occurs, there would be more gamma rays produced than appear in the spectrum according to the researchers' calculations. Similarly, if the region of acceleration is moved either farther from or closer to the Crab pulsar, the telltale gamma ray spikes also move and change shape. In other words, while the general picture is motivated by underlying physics, the specific details of the model are determined by adjusting parameters to make the spectrum fit the data.

Therefore, it should be emphasized that this is at present a plausible model for the production of high-intensity gamma ray pulses. As the authors recognize, further observations are needed to settle whether the pulsar wind acceleration and region of gamma ray production corresponds fully to what they propose. Nevertheless, enough concrete predictions are made by this model to compare to alternative explanations for the gamma ray spectrum, so additional data should be able to resolve which—if any—of the proposed theories truly explain what is seen in the Crab Nebula.

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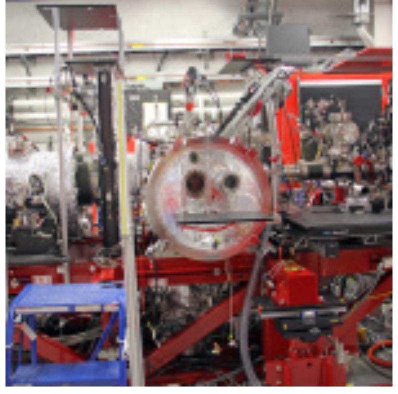

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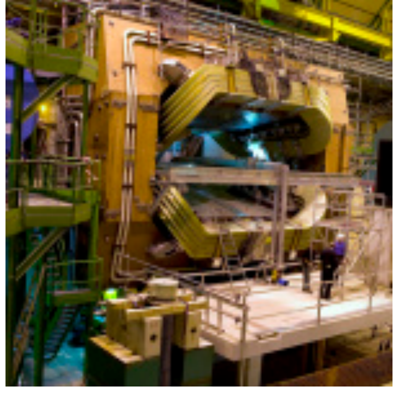

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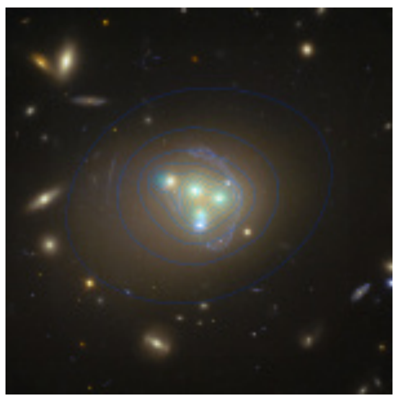

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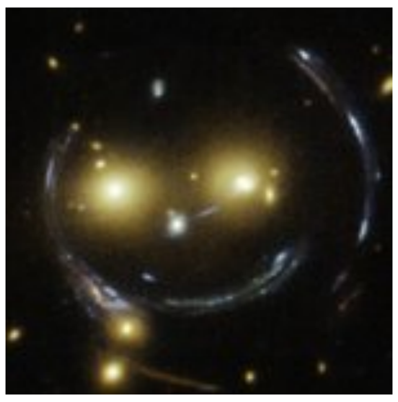

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