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Gamma-ray telescopes reveal powerful flares from the Crab Nebula

The brief, surprising flares involved synchrotron radiation from 10^{15}-eV electrons. It's hard to account for such rapid acceleration of charged particles to such enormous energies.

The Crab Nebula is the remnant of a supernova near enough (six thousand light-years) to have been noticed and recorded by Chinese astrologers in AD 1054. At its center, the energetic pulsar to which the supernova explosion gave birth continues to power the nebula's extraordinary luminosity across the spectrum from radio to TeV gammas. Seen from Earth at visible wavelengths (figure 1), the still-expanding nebula now subtends an angle of 5 arcminutes, corresponding to a width of about 10 light-years.

The Crab is arguably the most exhaustively studied celestial object beyond the solar system, and the apparent stability of its luminosity at all wavelengths has made it an attractive reference for calibrating observing instruments. The brightness of other objects is often quoted in "millicrabs." But the startling observation of a powerful gamma-ray flare from the Crab last September belies that vaunted stability, and it challenges the accepted theory of how charged particles are accelerated inside supernova remnants. That theory has its beginnings in Enrico Fermi's 1949 attempt to explain the origin of cosmic rays.

On 22 September, an announcement from the team that runs the Italian Space Agency's orbiting *AGILE* gamma-ray telescope alerted other observers that *AGILE* had just recorded a sudden flaring of gammas with energies above 100 MeV from the Crab Nebula. "The discovery felt like a punch in the nose," recalls Marco Tavani (University of Rome), leader of the *AGILE* team.

The next day, Rolf Buehler (SLAC) and coworkers in NASA's *Fermi Gamma-Ray Space Telescope* collaboration announced that *Fermi* had also recorded the flare. Now in back-to-back papers,[1,2] the two teams have presented their analyses of the flare data and follow-up observations. The flare, they report, lasted three or four days, and the energy range of the flaring gammas extended at least up to 1 GeV (see figures 2 and 3). Above 300 MeV, the flare produced a roughly sixfold enhancement in the Crab Nebula's nonpulsed energy spectrum.

The pulsar and its wind

The Crab pulsar is a neutron star, only about 10 km across, wrapped in a magnetosphere that extends out a few thousand kilometers. Together they spin with a 33-millisecond period. Because the magnetic and spin axes are misaligned, observers see the direct output of gammas and lower-energy photons from the compact star and its magnetosphere as a pulse train with 33-ms periodicity. But that direct, pulsed output of photons from the pulsar's immediate vicinity accounts for only a fraction of the quiescent Crab's total luminosity.

The nebula's nonpulsed luminosity originates much farther out. It's thought to begin at the terminal boundary of a magnetized plasma wind of relativistic electrons and positrons blowing from the magnetosphere. (Though created as e^-e^+ pairs, they're collectively called "electrons" for short.) The electron wind is invisible until it runs into the quasi-static "termination shock front," 10^{12}–10^{13} km (a few light-months) from the pulsar, where the wind pressure has fallen to that of the surrounding nebula.

At the shock front, a fraction of the impinging electrons are accelerated to energies high enough that their synchrotron radiation in the nebula's milligauss magnetic field accounts for most of the Crab's nonpulsed quiescent spectrum of x rays and gammas below the trough near 1 GeV in figure 3. Beyond that trough, the spectrum is well described by inverse Compton scattering—the boosting of photon energies by collisions with high-energy electrons.

In figures 2 and 3, the pulsed component of the gamma flux has been excluded, and yet the flaring is obvious. By contrast, the Crab's pulsed component (not shown) exhibited no irregularity of period or intensity during the flare. Therefore, even though the angular resolution of the gamma telescopes is insufficient to localize the source of the flaring gammas to a specific neighborhood within the nebula, "it's clear that they did not originate in the pulsar's immediate vicinity," says Stanford University theorist Roger Blandford, a member of the *Fermi* team.

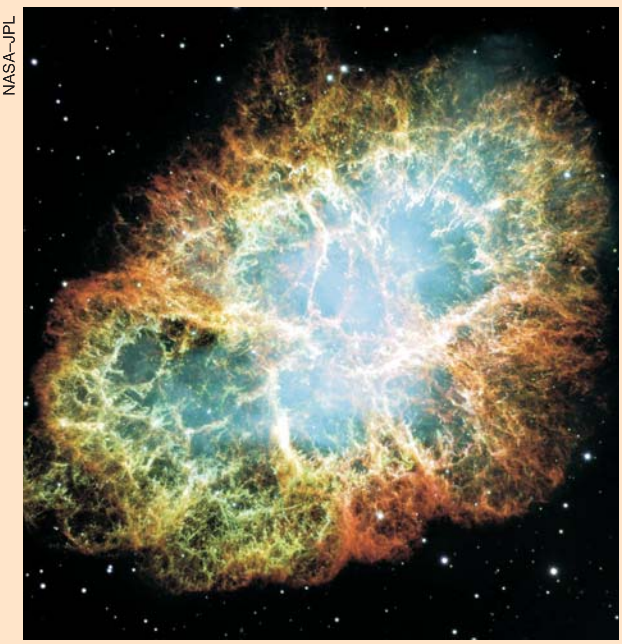

Figure 1. The Crab Nebula as imaged by the *Hubble Space Telescope* in 2005. False colors (red, dark blue, and green) around the periphery indicate emission by various ionization states of oxygen and sulfur in the still-expanding ring of ejecta from the AD 1054 supernova explosion. The ejecta ring encloses a large region of very low matter density, where visible light is dominated by synchrotron radiation (shown light blue) from electrons and positrons spiraling in the nebula's milligauss magnetic field.

The acceleration puzzle

Having evolved from Fermi's 1949 conjecture, the conventional theory of how charged particles are accelerated at

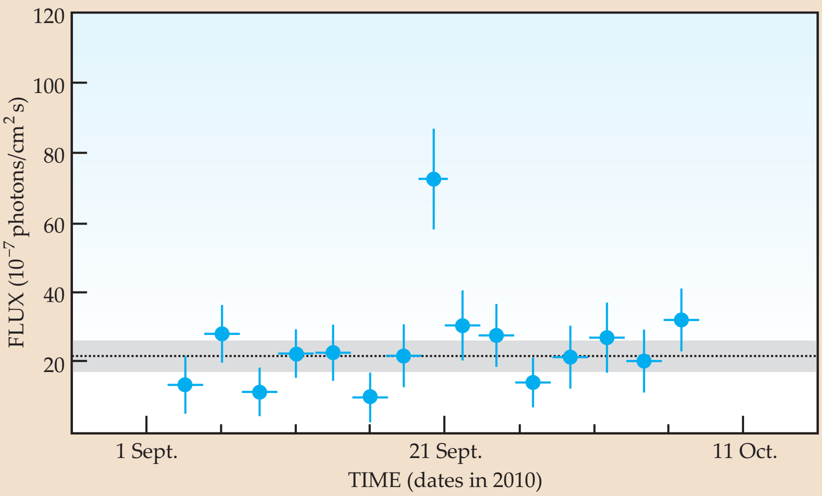

Figure 2. Temporal variation of the flux from the Crab Nebula of gammas with energies above 100 MeV, as observed by the *AGILE* orbiter, shows a dramatic peak around 21 September 2010. The flaring event was also recorded by the *Fermi Gamma-Ray Space Telescope* (figure 3). Detailed analyses by both teams indicate that the flare lasted three or four days. Excluded from the plotted flux is the 33-ms pulsed component attributed to direct radiation from the Crab pulsar and its corotating magnetosphere. The pulsed component showed no flaring. The dotted line is the long-term quiescent mean. (Adapted from ref. 1.)

shock fronts in supernova remnants is called diffusive shock acceleration (DSA). It posits that charged particles can be gradually accelerated to very high energies in small stochastic steps as they bounce back and forth in a random walk between magnetic mirrors at a shock front. Those mirrors are Alfvén magnetic plasma waves excited by the interaction of the shock with traversing plasma. The iterative acceleration process is very slow, and it has to compete with various modes of radiative cooling that decelerate the particles ever faster as they gain energy.

In principle, DSA can accelerate a tiny fraction of the electrons and positrons from the Crab's pulsar wind to the PeV (10^{15} eV) energies necessary for subsequent synchrotron radiation to produce GeV gammas. But certainly not with a rise time of days or weeks; the flare's onset would take years.

The flare's rapid fade, however, is consistent with the synchrotron cooling presumed for the gamma spectrum below 1 GeV, but not with the very much slower cooling rates of inverse Compton scattering. That's important because, as figure 3 shows, much of the flaring occurred in the trough between the synchrotron- and inverse-Compton-dominated components of the quiescent gamma spectrum. Knowing that even the GeV gammas of the flare are from synchrotron radiation reveals the highest energies to which electrons must have been accelerated in a matter of days.

"So the September flare was obviously caused by some acceleration mechanism very much faster than DSA," says *Fermi* team member Stefan Funk (SLAC). And its brief life restricts the region in which that mechanism operated to be no bigger than a few light-days (10^{11} km), probably a small patch somewhere on or near the termination shock. Whatever it is, the mechanism requires the brief local appearance of an accelerating electric field much stronger than is present in the quiescent phase.

"It might, for example, be a local plasma-wind instability at the shock," says Tavani, "or an instability at the magnetosphere that directs a temporarily enhanced wind at some particularly susceptible region of the shock front." Such plasma instabilities are not uncommon in tokamaks. How common might they be in the Crab?

Not the first, nor the last

It turns out that each gamma-ray telescope had recorded one previous flare from the Crab: *AGILE* recorded one in October 2007, just six months after its launch. The much larger *Fermi* telescope, launched the following year, recorded one in February 2009. Neither event had quite the spectacular suddenness of the September 2010 flare; each one lasted about two weeks. The teams had discussed the flares internally, but only now have they published them in the papers that reported the latest one. "If you've only seen one of something so unexpected, and don't know of any other sightings," explains Tavani, "you worry that it might have been an artifact."

Given the coverage history of the Crab by the two telescopes, the detection of three gamma flares thus far suggests that the Crab does it once or twice a year. If so, it will be interesting to see whether, as theorist Jonathan Arons (University of California, Berkeley) suggests, the recurrences are quasi-periodic. In any case, the Crab is now under close surveillance, not only by the gamma-ray telescopes but also by the *Hubble Space Telescope* and the *Chandra X-Ray Observatory*. With their much finer angular resolutions, the *HST* and *Chandra* could pinpoint anomalies to small structures within the nebula.

In fact, the *AGILE* team's paper[1] included follow-up observations by the *HST* and *Chandra* about a week after last September's flare, observations that show suggestive brightening of several structures near the terminal shock. "It's no smoking gun," says Tavani, "but they might be afterglows at longer wavelengths."

"Our way forward is clear," says Blandford. "The new monitoring regime should let us see if any local structures are brightening in x rays or the visible *in coincidence* with the next gamma flare. That would be an important clue for theorists."

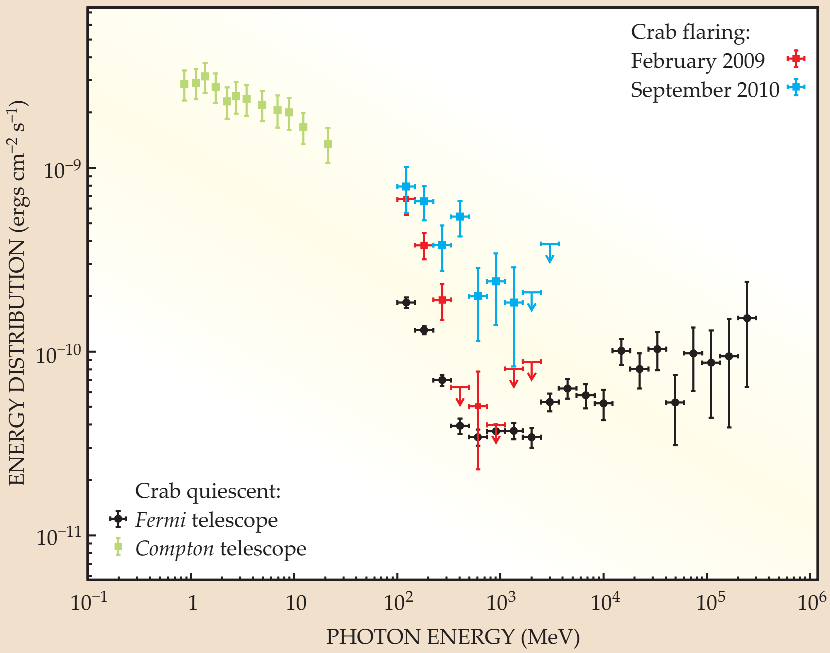

Figure 3. Spectral energy distribution of gammas from the Crab Nebula with energies above 100 MeV, as recorded by the *Fermi Gamma-Ray Space Telescope* in the nebula's normal quiescent state and during two gamma flares. (Arrows indicate upper limits.) The trough near 1 GeV in the quiescent spectrum is thought to indicate the divide between sub-GeV gammas produced by synchrotron radiation and the higher-energy gammas produced by inverse Compton scattering. The points below 20 MeV are older, quiescent-state data from the *Compton Gamma-Ray Observatory*. As in figure 2, the 33-ms pulsed component is excluded from all the plotted spectra. (Adapted from ref. 2.)

A unique laboratory

The Crab is the only place where relativistic astrophysical phenomena can be studied with the requisite spatial and temporal resolution. Aside from its proximity, the Crab also has the virtue of neatness—as supernova remnants go. Some supernovae leave behind a black hole rather than a neutron star, and the remnant nebula is powered by messy and often episodic accretion of nearby material. The Crab Nebula, by contrast, harbors very little baryonic material, and its luminosity is powered almost entirely by the steady but very gradual slowdown of the pulsar's spin.

Supernova remnants are thought to be the principal intragalactic source of cosmic rays. But the scarcity of protons in the Crab Nebula means that it is, at best, a feeble cosmic-ray source. That's probably true of most pulsar-wind nebulae. "But they're excellent laboratories for studying the physics of acceleration associated with relativistic outflows," says Arons. Relativistic outflows from active galactic nuclei, for example, are conjectured to be the principal extragalactic sources of cosmic-ray protons with energies above 10^{19} eV. But no observation has as yet been able to assign such ultrahigh-energy particles to any specific source.

In that regard, the data from the Crab's September flare set a new record: The flare's spectrum and its fast decay make it clear that the flaring GeV gammas come from synchrotron radiation by electrons that have somehow been accelerated to 10^{15} eV. "Those PeV electrons," Buehler points out, "are the highest-energy particles anyone has yet been able to associate with a specific astrophysical object."

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References

1. M. Tavani et al. (AGILE collaboration), *Science* **331**, 736 (2011).
2. A. A. Abdo et al. (Fermi collaboration), *Science* **331**, 739 (2011).

Time reversal produces optical focusing in scattering media

A technique hatched from concepts in acousto-optics and phase conjugation could be ideal for biomedical imaging and therapy.

A focused beam of light can trap a colloidal sphere, cause a specific neuron to fire, or deliver a lethal dose of energy to a cancerous cell. In biomedicine, focused light can perform nearly all the same sensing, diagnostic, and therapeutic functions as targeted x rays, without inducing harmful ionization.

Delivering light to internal tissue and organs, however, is not a straightforward task. In air or other transparent media, optical focusing is a simple matter of geometry—shape a beam with a curved lens and its rays will converge on ballistic trajectories toward a target. Scattering media such as biological tissues are not so cooperative. At penetration depths much larger than the scat-