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Scientists search for supernova's pulsar

The neutrino burst from Supernova 1987A marked the formation of a neutron star within it. But is it a pulsar? David Cherry reports on this extreme condition of matter.

A quiet drama is now unfolding in the study of SN1987A, the star in the Large Magellanic Cloud, a satellite of our galaxy, that exploded into a supernova in February 1987. Scientists are now engaged in the search for a pulsar possibly left behind by the exploding star. A pulsar is a neutron star, a tiny star of inconceivable density, that sends out a powerful lighthouse beam as it rotates.

One key in the study of the universe is the behavior of matter under extreme conditions. The tiny pulsar gives us access—albeit limited access—to some very extreme conditions.

The pulsar, if it is a pulsar, may be discovered through detection of its very high energy gamma rays in the coming months, or, failing that, through low energy gamma rays that we probably won't see for a few years. Longer wavelength radiation will peek through the supernova's thinning envelope even later. Scientists operating cosmic ray detectors across the southern hemisphere are already looking for the very high energy gammas.

It will be the first time that a pulsar has been detected virtually at birth, and the pulsar may produce—in combination with the exploded envelope of the original star—"a little Crab Nebula," in the words of Alice K. Harding, a pulsar theorist at the Goddard Space Flight Center (see interview). The Crab Nebula, remnant of a supernova explosion almost a thousand years ago, is continuously lit by the energy from the pulsar within it (see **Figure 1**).

That pulsar in the Crab Nebula, one of the first pulsars to be discovered, was found in 1968. But the story more properly begins in 1933, when Walter Baade and Fritz Zwicky first distinguished the supernova phenomenon from that of the much less cataclysmic nova. They soon found by computation that the supernova process might leave behind a previously unknown creature. They called it a neutron star. The supernova, they said, could be triggered by the collapse of the star's core, when fusion in the star began to exhaust its sources of fuel (see *EIR*, Science & Technology, March 18, 1988). The outward flow of radiation from fusion would die down and cease to counterbalance the gravitational pull, according to theory, and the core would collapse. Gravitation would become so overwhelming that electrons would no longer hold their orbits, but would merge with protons to form neutrons. Having no charge, neutrons would not repel each other, and would pack densely. The result would be a sphere with a diameter of 10 or 12 kilometers, but with the mass of the Sun! One cubic centimeter of pure neutronic matter would weigh as much as all of humanity. The neutron star is at least the generally accepted conception of the outcome of the core collapse process.

It *is* beyond the casual imagination. Moreover, a sphere 12 km in diameter is too small to be seen with the best telescopes at interstellar distances. Yet, what we know *from observation* about Sirius, the Dog Star, enables us to contemplate the existence of a neutron star with equanimity. Sirius is a binary system of two stars in orbit about their common center of mass.

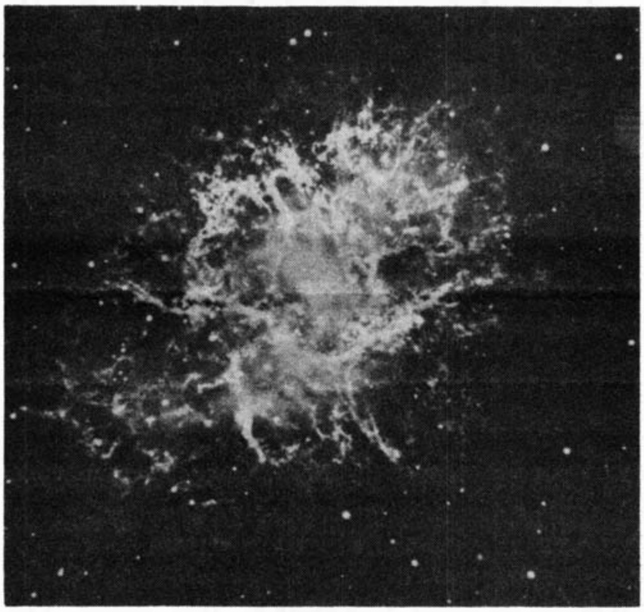
Thanks to Kepler's laws and a combination of fortunate circumstances, it has been possible to determine the density of its two components. The undoubted result is that one of the two stars, a white dwarf, has a density of 1 million grams per cubic centimeter. The greatest density we know on Earth is about 20 grams per cubic centimeter! And pulsars are much denser than white dwarves.

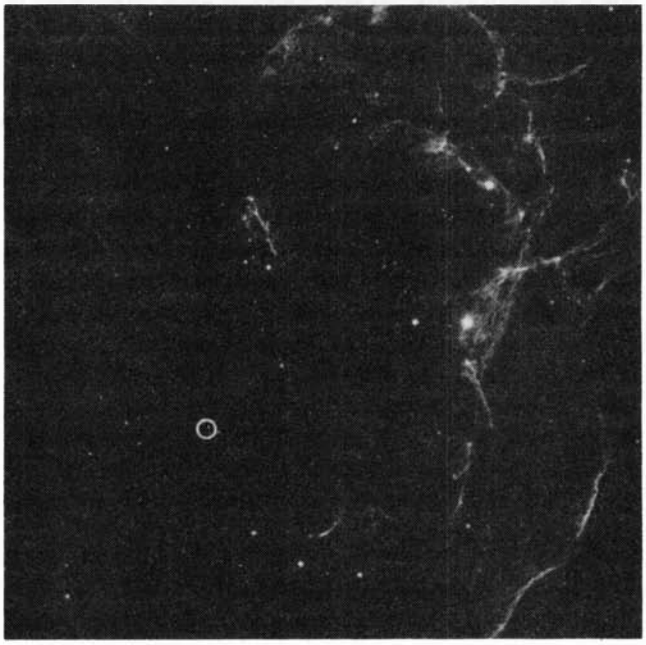
Baade and Zwicky's hypothesis that some types of supernovae left neutron stars behind, although very interesting, had no known observational reference point in 1934. It was not until 1967 that a "neutron star" was suddenly required to account for an unprecedented observation.

That observation was the work of Cambridge University graduate student Jocelyn Bell, who participated in building a large radio telescope under the direction of Anthony Hewish. Hewish was interested in studying the scintillation of radio

FIGURE 1

Three nebulae remnants of supernovae associated with pulsars





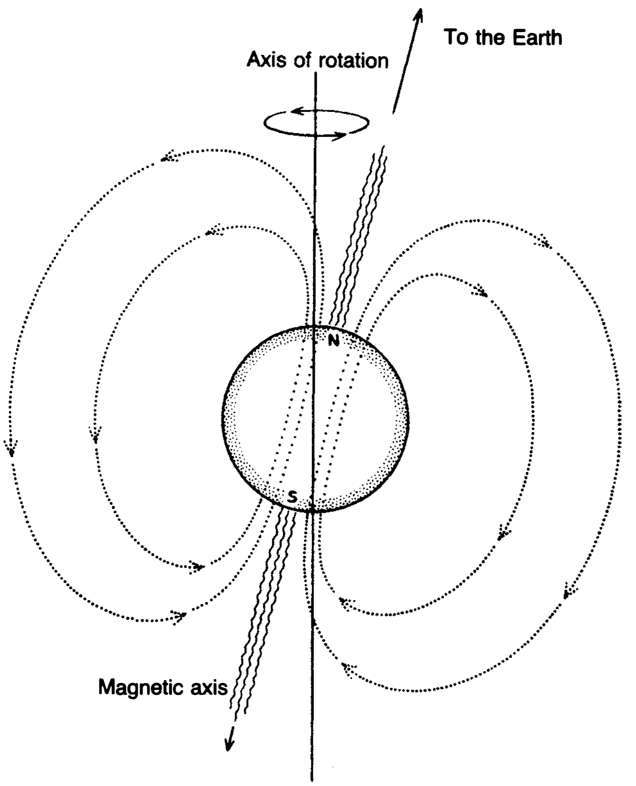
More than 120 nebulae in our galaxy have been identified as the remnants of supernovae. Yet, there are only three cases (shown here) in which a pulsar can be associated with a nebular remnant, since Earth must lie in the path of the beam for the pulses to be seen.

At upper left is the Crab Nebula, remnant of a supernova that exploded less than a thousand years ago, in 1054. It emits energy all the way from radio waves to gamma rays, lighting up the surrounding remnant nebula. Upper right, the gaseous Nebula IC 443 in Gemini. Its association with pulsar 0611+22 is open to question. Lower right, part of the Gum Nebula in the constellation Vela. The location of the pulsar is marked with a small circle. Approximately 10,000 years after the supernova event, this pulsar has a period of 0.0892 seconds. A fourth association between a pulsar and a supernova remnant—called the Crab Nebula Twin—was identified in 1984 in the Large Magellanic Cloud beyond our galaxy.

Sources: upper left, Lick Observatory; upper right, Hale Observatories; lower left, B.J. Bok.

FIGURE 2

The oblique rotator model of the pulsar



What physical configuration could give rise to short, frequent, regular pulses? Expansion and contraction of the object is ruled out—pulsar periods are too short for expansion and contraction to be accomplished. What if the object emitted a beam of light on one axis while rotating on a different one? Then an observer in the path of the beam would see a pulse on each rotation. (The Earth itself provides an example of the axis of rotation and the magnetic axis being different.) These considerations have given rise to the standard model shown above. Some theorists think the beam is not collinear, but is itself a hollow cone whose axis describes a cone during rotation.

Source: George Greenstein, *Frozen Star,* 1983, p. 74.

waves coming from quasars—scintillation caused by the interplanetary medium. Bell was in charge of taking all the data, and noticed the appearance of recurrent blips made by the recording needle every time the antenna was pointed toward a certain part of the sky.

Radio telescopes of the day were not equipped with the means to sample the signal in fine slices of time, since rapid fluctuations were not expected from astrophysical sources. In fact, time constants of several seconds had the advantage of smoothing out fluctuations in the background noise. But for purposes of studying scintillation in the interstellar medium, a time constant of 0.1 second was necessary, and this was the first telescope equipped to accomplish that.

Bell noticed radio pulses that kept coming, one and one-third seconds apart, with varying amplitude. The clocklike precision in the timing of the pulses caused Hewish and his colleagues to conclude that the signals must either be man-made (such as from space probes), or else produced by other intelligent beings from somewhere in space—"little green men," as they were jokingly called. Both ideas were reasonable enough.

Bell—less fixed in her ideas of what to expect from the stars—didn't see why the source could not be astrophysical. She turned out to be right.

The small parallax of the source proved that it had to be far out in space, and hence, not man-made. If it was being beamed from a planet in another solar system, there would be Doppler shifting as the planet's rotation caused the source to approach and then recede from the Earth—but there wasn't any. When Hewish and Bell published their initial report in *Nature* on Feb. 24, 1968, they included a model based on the idea of beamed radiation coming from a white dwarf or neutron star that was rotating with a period equal to the time between pulses (see **Figures 2-3**). The rapid-fire detection by Bell of three more widely separated sources of such radio pulses gave impetus to the idea that the phenomenon was astrophysical in nature.

The theory of the pulsar that survived—when tested against a cascade of new pulsar discoveries—was that of the Austrian-born astrophysicist Thomas Gold. In 1968, Gold proposed that the pulsar was a rapidly spinning neutron star with a high magnetic field on the order of 10^{12} gauss that spins with it. The neutron star results from the collapse of the core of a star, he said, whose magnetic field is compressed when the core collapses, and whose angular momentum is conserved, causing the neutron star to "spin up" at the time of the core collapse. Gold predicted that pulsars should subsequently spin down very slowly, owing to the conversion of their spin energy into emitted radiation, and this has been confirmed by observation.

The discovery of pulsars at the centers of supernova envelope remnants completed the broad outlines of the picture. The most exciting of these was the discovery in 1968 of a pulsar in the Crab Nebula with a period of only 33 milliseconds, making it the fastest, and hence probably the youngest, pulsar known. The Crab Nebula is known to have been created by a supernova that exploded in 1054. Within months, it was found that the Crab pulsar was also emitting pulses of optical light, and that it coincided with the star that Baade had identified as the remnant of the supernova that fathered the Crab Nebula. Baade had seen the pulses as continuous emission (see **Figure 3**).

Model for the beamed emission

The standard model of a pulsar is the *oblique rotator* shown in Figure 2. The spin axis of the neutron star in the general case does not coincide with the magnetic axis. The beam is thought to be produced in alignment with the magnetic axis. Collimated streams of charged particles are ejected from the magnetic poles at a significant fraction of the speed of light, and emit beams of continuum radiation, in many cases all the way from radio waves to gamma rays. The model is reminiscent of the free electron laser. This configuration causes the beam to sweep out a hollow cone as the star rotates. For an observer in the path of the beam, the time between successive pulses is equal to the rotational period of the star (see Figure 3).

Physically, how can this model be made to work? Astrophysicist and pulsar student George Greenstein, in his popular book, *Frozen Star* (1983), takes us part of the way there. He begins with the fact that a rotating magnetic field produces an electric field and a flow of charges. He considers two particles lying on the surface of the neutron star:

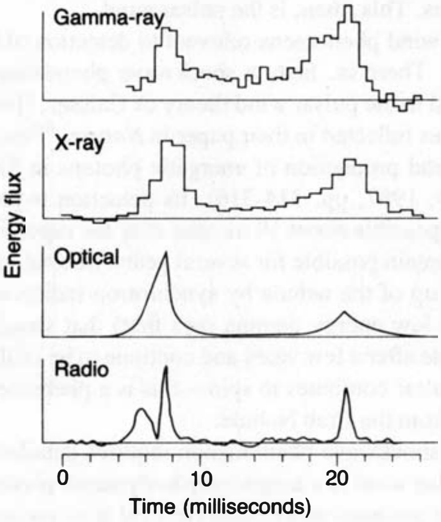
> [T]he first will lie at the north magnetic pole, the second somewhere along the magnetic equator. An electric field acts to lift both of them away from the star. The charge at the magnetic pole is free to move, and it accelerates vertically upward along a line of force. But the second charge is not free to move outward. If it were to do so, it would cross a magnetic field line, and this is forbidden. The motion of the charges is beamed. So is the radio emission [that is created by the charges].
>
> A more careful analysis shows that the acceleration is strong only for particles located quite close to one or the other of the two magnetic poles. So the picture naturally accounts for the narrowness of the pulsar beacon. [Does it? Is the radio emission produced over a significant length of an open field line? How straight is that length of field line?] . . . [O]ne is forced to postulate some bunching mechanism to account for observed pulsar intensities. . . . The picture might be made to work. *(p. 73)*

Greenstein reports the *observed power* of the pulsar beam in this way:

> What words can never convey is a full appreciation of the intensity of this beacon. Nothing on Earth even

FIGURE 3

The integrated profile of the Crab pulsar signal from radio to gamma-ray frequencies

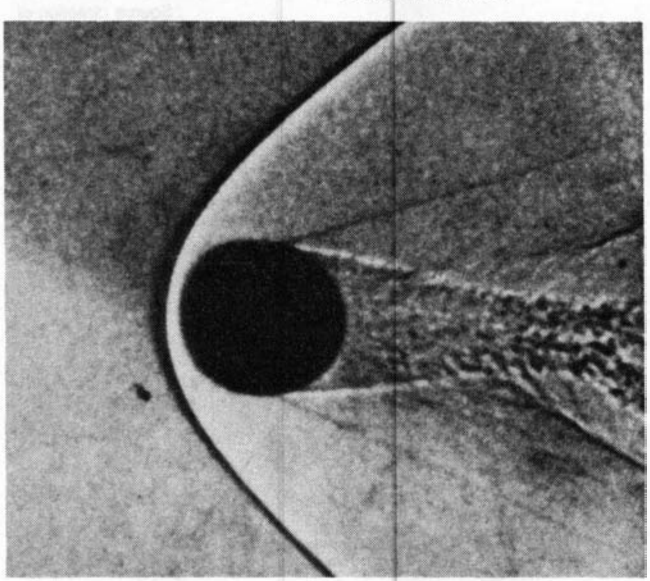


The integrated profile of the Crab pulsar signal, representing the averaging of numerous pulses. The Crab pulsar has a period of 0.033 seconds. Pulsars characteristically have a main pulse (left) and a second pulse of less intensity called the interpulse (right). The interpulse phenomenon has not been adequately explained. While individual pulses vary slightly in shape and timing, the integrated profile of even a few pulses is as characteristic of the particular pulsar as a fingerprint. What allows the pulses to vary, but always average to the same profile?

Source: R.N. Manchester and J.H. Taylor, *Pulsars,* 1977, p. 70.

FIGURE 4

Čerenkov radiation and shockwaves



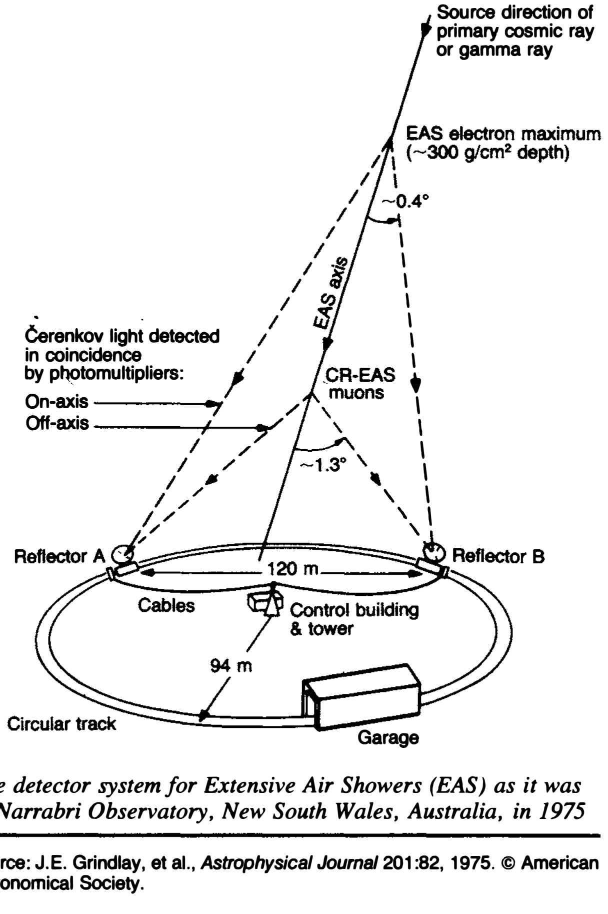
When a charged particle traverses a medium at greater velocity than the speed of light in that medium, *it emits light at visible wavelengths in a shockwave. This is called Čerenkov radiation. The particle continues to lose energy by radiation until it reaches the speed of light for the medium. A Čerenkov detector may have a specially chosen medium in it to trigger the emission of the radiation, or may rely upon the atmosphere itself as the trigger. Čerenkov radiation is analogous to the bow shockwave produced by a body traveling through air at supersonic speed, shown above.*

remotely approaches such an intensity. The pulsar searchlight beam is so strong that were a person to venture within a hundred million miles, he would be killed—killed by mere insubstantial radio signals—in a fraction of a second. Close to a pulsar, the radio beacon is sufficiently powerful to vaporize metal and bore holes through solid rock. In a single second, this beam transmits enough energy to supply the energy requirements of our entire planet—transportation, heating, industry, for Europe and America and all the rest of the world combined—for a full 300 years. *(p. 60)*

Were Earth to lie in the path of this beacon, we would have no difficulty in seeing it. We see the Crab Nebula Twin that also lies within the Large Magellanic Cloud, despite a distance of about 170,000 light years. On the basis of simple probability, Earth is more likely not to lie in its path. How, then, can we detect it?

FIGURE 5

The detector system for Extensive Air Showers (EAS)



The detector system for Extensive Air Showers (EAS) as it was at Narrabri Observatory, New South Wales, Australia, in 1975

Source: J.E. Grindlay, et al., *Astrophysical Journal* 201:82, 1975. © American Astronomical Society.

Despite the stupendous power of a pulsar beacon, calculations show it can be carrying off only 1%, or a fraction of 1%, of the pulsar's total spindown energy. Meanwhile, as seen in the case of the Crab Nebula, a supernova remnant nebula is apparently kept bright by some large amount of the spindown energy. How is this energy transferred? In the last few years, magnetohydrodynamic wind models of the pulsar—on the analogy of the solar wind—have been developed to explain how the greater part of the spindown energy is carried off and deposited in the nebula.

The pulsar wind—and detection

The wind phenomena are the key to detection because the wind comes off in all directions. How is the wind formed? Magnetic dipole energy is its source. The rapid rotation of the strong magnetic field would produce magnetic dipole radiation if the star were in a vacuum. If one rotates a dipole—for example, a bar magnet with positive and negative poles—in a vacuum, it will give off radiation having the frequency of the rotation. That is magnetic dipole radiation, also known as radio waves. It seems clear, however, that the star is surrounded by plasma of sufficient density to prevent the propagation of this radiation, and the result is the conversion of that energy into electron and positron pairs. Perhaps they stream out only along the open field lines initially; but the rapid rotation of the magnetic field causes the lines to wind up, so that the electrons and positrons are sent out in all directions. This, then, is the pulsar wind.

The wind phenomena relevant to detection of the pulsar are two: There is, first, a shockwave phenomenon that is predicted in the pulsar wind theory of Gaisser, Harding, and Stanev (as reflected in their paper in *Nature,* "Particle acceleration and production of energetic photons in SN1987A," Sept. 24, 1987, pp. 314-316). Its detection is predicted to become possible about 18 months after the supernova event, and to remain possible for several years. Second, there is the lighting up of the nebula by synchrotron radiation (we will see it in low energy gamma rays first) that should become detectable after a few years and continue to be visible as long as the pulsar continues to spin—this is a phenomenon well-known from the Crab Nebula.

The shockwave phenomenon requires detailed analysis. The pulsar wind is a magnetohydrodynamic plasma of electrons and positrons propagating outward at relativistic speed—some significant fraction of the speed of light. It is confined, however, by the supernova envelope, since the envelope is expanding more slowly than the wind. Where the two meet, a standing shockwave forms—a discontinuity of velocity and density. The pulsar wind piles up against the inside wall of the supernova envelope. According to theorist Harding and her co-authors, protons and electrons are accelerated within this discontinuity.

The phenomenon is apparently analogous to the trapping of a bouncing ping-pong ball between paddle and table, when the paddle is brought down on the ball gradually—the ball oscillates faster and faster. In the region of the shock, however, the particles are accelerated without remaining trapped. With a range of velocities acquired in this manner—in the teravolt and petavolt range (10^{12} and 10^{15} electron volts, respectively)—the particles eventually penetrate the envelope. The accelerated protons are of primary interest from the standpoint of detecting the pulsar. Harding and her co-authors calculate that "if a proton beam of power $\sim 10^{40}$ erg/sec and spectral index $\gamma \leq 2.6$ were accelerated at SN1987A, an observable γ-ray signal would be produced."

While the envelope is sufficiently young and therefore still dense enough, there will be a significant collision rate between the accelerated protons, and nuclei in the envelope, producing neutral pions (unstable particles of mass intermediate between that of protons and electrons) that quickly decay into two TeV gamma rays each. But at too early a time, the envelope is *too* dense to allow the gamma rays to get out to be observed. Hence, there is only a window for observation, beginning perhaps 18 months after the supernova event. (If the pulsar is very energetic, spinning faster than 100 times a second or so, we should expect to be seeing them even now.) After five or ten years, however, the envelope will have thinned out to the point that the collision rate drops, and the production of gamma rays falls below the observable threshold.

These very high energy gamma rays are to be observed—but still not directly. When they hit Earth's atmosphere, they trigger a photomultiplier of nature's own devising called an extensive air shower (EAS). The gamma ray collides with molecules of the atmosphere, setting in motion a cascade of secondary radiations and particles that spreads in chain reaction fashion until it reaches the Earth's surface. There we are ready for it with particle detectors and Čerenkov detectors (see **Figures 4 and 5**). Čerenkov detectors capture the flashes of Čerenkov light with mirrors that focus it onto photomultiplier tubes. The energy and direction of the initiating gamma ray can be deduced from what the detectors pick up. Čerenkov detectors now use multiple mirrors to actually image the shower with one-degree resolution.

Successful detections of these gamma rays would not only establish the existence of a pulsar in Supernova 1987A, but would confirm a good deal of the pulsar wind and shockwave model that predicts them. That would be a wonderful outcome that could tell us much about these extreme conditions in nature.

Should these observations not materialize, there is still the possibility of detecting the pulsar a few years from now, when the envelope has thinned out enough to let through the synchrotron radiation—the radiation given off by electrons in the pulsar wind as they spiral around magnetic field lines. This is the radiation that lights up the Crab Nebula for us to see, and this is the most certain means of confirming the presence of a pulsar in Supernova 1987A.

Interview: Alice K. Harding

SN1987A: Eventually a small Crab Nebula

Alice K. Harding is an astrophysicist and pulsar theorist at NASA's Goddard Space Flight Center in Greenbelt, Maryland. This interview began on March 25, and was continued on April 21.

EIR: You are predicting the appearance of very high energy (VHE) gamma rays from the supernova sometime in the coming weeks and months, as a result of the expected pulsar. I gather there are some significant uncertainties in this.

Harding: Yes. It's really not guaranteed. First of all, although we believe there's a neutron star there, whether or not it will be spinning fast is not known. We assume it's going to be spinning at least as fast as the Crab pulsar, but nobody has seen it happen before, so we don't really know for sure. And if it's a pulsar spinning fast, then is this wind model correct? Does energy go into relativistic particles? And *that* seems to be happening in the Crab pulsar. So if there is a pulsar in the center of this thing, we're sure to get some kind of relativistic particles.

EIR: Because these particles are being scattered in all directions out of the wind?

Harding: Theoretically, it happens because the wind forms a shock. It's not clear how the particles are accelerated, actually, in these models. But the picture we have is that there is a shock that forms in the nebula, within the envelope, and that shock accelerates particles by scattering them back and forth across the shock, which is a discontinuity in velocity and density. The mechanism is that if you scatter back and forth across a velocity discontinuity, it's as if you are bouncing particles back and forth between converging walls. That boosts them up to high energies.

EIR: So we're talking about basically two concentric spheres which are converging, and it's the space between the spheres. . . .