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 $\gamma \leqslant 2.6$ 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. . . .

Harding: . . . and the particles essentially bounce between them, because of the irregularities in the magnetic fields. The particles scatter off of those irregularities. So they can bounce back and forth across the shock many times. The particles that bounce back and forth the most gain the most energy. You get a whole spectrum.

EIR: So, that means the particles are going to come out in all directions?
Harding: They should come out pretty much in all directions downstream of the shock. They should be able to diffuse into the envelope which is further out. This is the original envelope of the star that was blown off. We expect that there are electrons being accelerated by the shock—there are also protons that are accelerated, and those protons can interact to make the high energy gamma rays. But there are a lot of questions along the way here: Is this really shock acceleration? If it isn't, there are other ways that you could accelerate electrons and not protons. In that case, you might get low energy gamma rays, but you wouldn't get these very high energy ones. So, that's one question.

Second, if there are protons being accelerated, can they, in fact, diffuse into the material of the envelope, or do they stay near the shockwave, where there is not much material for them to interact with? They might actually be confined very close in to the shock. These are details that we are working on right now, but the general picture is that there is enough mixing of the envelope into this region where the accelerated particles are, that there should be some high energy gamma rays, if you do have accelerated protons. So there are several "ifs," but it's a strong possibility that there is a pulsar present.

EIR: Are you working from the textbook model of the oblique rotator?
Harding: That's the model we're assuming. The basic model is that you have a neutron star with a dipole field that is not aligned with the spin axis. So, you get a spindown of the star which appears in some form of energy. The old model was that it appeared as electromagnetic dipole waves, which would be radiated off as concentric spherical waves into space. But that's only true in a vacuum. It turns out that when you have a lot of surrounding material, these dipole waves don't propagate, because they are below the plasma frequency—like radio waves that bounce off the ionosphere when they are of too low a frequency. So, instead of that, they get absorbed, and the energy gets carried off in a wind with particles in a magnetic field, something like the solar wind. That's more or less the present picture of how the spindown energy of pulsars gets carried off.

EIR: These gamma rays will be coming out in all directions. Where does the beamed energy come into the picture that gives the pulsar its name?
Harding: There are two different kinds of radiation here. The beamed radiation is the one that forms the pulses at radio, optical, x-ray, and gamma-ray frequencies. That radiation is at a much higher frequency than this dipole radiation, which, in the case of the Crab pulsar, is at 30 Hertz [30 cycles per second]. It's actually at the frequency of the spin of the pulsar, so it's very low frequency radiation. The amount of energy carried off by those very low frequency waves is much greater than the energy emitted as higher frequency radiation that you see in pulsed form.

EIR: Why is that?
Harding: It has something to do with the efficiency with which the pulsar converts its spindown energy into higher frequency radiation. It just isn't very efficient at converting its spindown energy to radio emission. In fact I think the radio accounts for only—what is it—10^{-5} or less of the total spindown power. Even the gamma-ray emission, which is the highest-efficiency process, is only about 10^{-3} of the total emission. So what you see in pulsed emission is really kind of a small blip. It's just that it's [in a form that is] a lot easier to see.

EIR: So, what kind of conversion is there that causes this 30 Hz radiation to become detectable to us? Is that tied to what you were saying about particle acceleration at the shock boundary?
Harding: In the Crab pulsar, if you look at the nebula, you see very strong synchrotron emission. That total energy in synchrotron emission is roughly equal to the spindown power of the pulsar. So, somehow, the Crab pulsar is converting, with something like 20 or 30% efficiency, that spindown energy into relativistic electrons. If there were protons in the Crab Nebula, we wouldn't see them, because the density of the nebula right now is much too low for the protons to interact. So, the only way to see protons is from a very young supernova remnant, like 1987A, where the envelope is still dense enough, so that those protons can't just escape, or diffuse around forever. They have to interact. And if they interact, they produce the gamma rays. So, that's the chain of argument. . . .

EIR: We know—or at least we think we know—that there has to be a neutron star there.
Harding: Yes—the neutrino burst [confirms that]. . . .

EIR: The next question, therefore, is whether that neutron star is a pulsar. We can't count on the pulsed—that is, the beamed—energy to give us the answer. We might not lie in the beam's path. Is there any distinguishing phenomenon of a pulsar that carries a very high probability of happening and being detected?

Harding: Yes. I think a very high probability would be the relativistic electrons, as in the Crab Nebula. If there is a pulsar, ultimately we should see the effects of something like 20-30% of the spindown energy in relativistic electrons, in the form of synchrotron radiation. We predicted what this would look like in our paper as well [at the February 1988 meeting of the American Astronomical Society in Austin, Texas, and in *Nature,* Sept. 24, 1987]. Since it's not as dramatic, it didn't get mentioned in the press articles—the dramatic stuff is the high energy gamma rays—but certainly you should expect synchrotron radiation at about 10 MeV, or 1 to 10 MeV, from the electrons.

EIR: Well, that's pretty dramatic to *my* mind.
Harding: Yes, yes. You would see something emerging eventually that looks like a small Crab Nebula. . . .

EIR: Under what conditions are supernova remnants called "Crab-like"?
Harding: When there is a pulsar at the center. "Crab-like" means it's a pulsar surrounded by a synchrotron-emitting nebula. There are about three or four of these, and they all seem to conform to the same type of model—relativistic electrons appear and agree in some fairly good way with the spindown energy of the pulsar. So, we would expect this supernova, if there is an active pulsar there, to become a Crab-like remnant eventually. That is, when all the rest of the envelope becomes optically thin to what's going on down in the center. In the radio range, that's going to take a long time, but at higher energies—x-rays and gamma rays—it may only take a few years. . . . All of this is very model-dependent. Right now, SMM [Solar Maximum Mission] is looking for continuum emission between 1 and 10 MeV. Certainly, it doesn't hurt to look now, because we don't know exactly when it will become visible.

EIR: Sure. Our predictions were very wrong about the time of appearance for the x-rays and the nuclear gamma rays.
Harding: The gamma-ray lines [that establish explosive nucleosynthesis], by the way, are now doing something completely unexplainable in terms of the standard model. They seem to be decreasing—turning off—as of the latest IAU Circular. All the models say the peak is yet to come. So, we don't really know what's going on with this envelope, and I don't think we've seen the last word on the model. So I don't know exactly what to say. I really can't predict when these relativistic electrons—the radiation from them—will appear.

The interview continued on April 21.

EIR: Is there any news regarding the detection of the VHE gamma rays since we spoke last?
Harding: Yes, there are some new upper limits [being established on the background flux]. They haven't been published, so they're tentative. But one was just reported at the meeting in Baltimore [the American Physical Society spring meeting the same week], by my colleague, Tom Gaisser, who is involved in the experiment with the air shower array at the South Pole, for detecting particles from the air showers. It is ideally suited to look for the supernova, because it's always up, and it's always at the same declination. Their threshold for detecting gamma ray showers is about 50 TeV, that's 5×10^{13} electron volts, and that's much lower than the other air shower particle detectors.

EIR: Lower than any other?
Harding: The other particle detectors are usually in locations which have higher backgrounds, and so their detection thresholds are always at higher energies. This one, since it's at the South Pole and at a high elevation—9,000 feet above sea level—has much less background. They have a very good upper limit. From just four days of data in February, when they turned on the detector—they just looked at over four days of the supernova—and they got an upper limit of 10^{40} ergs per second on the flux—the luminosity—of protons [at the source], so that's a new upper limit. They will be able to do 10 times better than that in a year, and they'll be looking at the supernova continuously. Another experiment is being conducted in Australia. They have an air Čerenkov detector, which detects visible light from the showers at lower energies. They are sensitive around 1 TeV, which is 10^{12} electron volts.

EIR: Who runs these arrays?
Harding: The one at the South Pole is a collaboration between Leeds University in England and Bartol Research Institute at the University of Delaware, where Tom Gaisser, one of my co-authors, works. The Australian one is run by a group at Durham University in England, headed by Ted Turver. They apparently have some new results that have not been published.

EIR: These arrays are working on limits for detecting the VHE gamma rays predicted in your paper?
Harding: They were not designed primarily for that, because they were built before the supernova, but over the next year they are going to be probably devoting a good part of their time—the time that they can *see* it—to looking at the supernova. Some cannot see it all the time. The air Čerenkov detectors rely on a dark sky—they can only look at night because they are detecting flashes of visible light. And they can only see the supernova for a few months at a time. The Durham group has been devoting 50% of the time that they can see the source, actually looking at it. It's a pretty big effort for probably the next year.