Pulsar puzzles for astronomers

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THE announcement in March this year by Kristian *et al.*¹ of the detection on 18 January of a pulsar in supernova 1987A with the phenomenal pulse rate of nearly 2,000 Hz stunned both observers and theorists. Almost all accepted theories of dense nuclear matter, from which pulsars are made, indicate that a pulsar spinning at this rate would rapidly disintegrate. This conclusion is borne out by calculations presented by Friedman *et al.* in *Physical Review Letters*², Shapiro *et al.* on page 451 of this issue³, and Haensel and Zdukun in a forthcoming paper⁴. But there remains considerable uncertainty about the interpretation of the observations¹, so it may be premature to abandon cherished models.

The burst of neutrinos seen with the original explosion of SN1987A strongly indicates that a neutron star was formed in the supernova, but no one expected it to be spinning so rapidly. Observations of other pulsars, especially those such as the Crab pulsar that are associated with supernova remnants, suggest that pulsars are born with relatively strong magnetic fields and pulse rates of not more than a few tens of hertz. Even for millisecond pulsars, which are believed to be very old and to have acquired their rapid spin through angular momentum transfer as a member of a binary system, the highest observed pulse rate is less than 700 Hz. The interpretation of the SN1987A pulsar as a neutron star rotating at the pulse rate puts a severe strain on models of neutron-star structure.

Stability

A stringent limit for the stability of a rotating neutron star is that its equatorial velocity be less than the orbital velocity at that radius — or material would be flung from the surface. Gravitational instabilities also set in at about this rotation rate. Because of the peculiarities of the equation of state of degenerate matter, more-massive neutron stars have smaller radii and so can spin more rapidly. But there is a limit to the mass of a neutron star beyond which it collapses to form a black hole.

Different equations of state have different mass-radius relations and different maximum masses. The new papers²⁻⁴ demonstrate that only the 'softest' equations of state (those with smallest radius for a given mass) considered so far are stable at rotation rates of 2,000 Hz and even then only for a very small mass range near the maximum. Interpretations of pulsar glitches and X-ray pulsars have favoured the stiffer equations of state. This dilemma is sharpened by the fact that the maximum mass for the soft equations of state is much less than 1.4 solar masses ($M_{\odot}$). The most accurate mass determina-

tion is for the binary pulsar PSR 1913+16 (ref. 5); both of the neutron stars in this system have masses close to $1.4 M_{\odot}$. In fact, all determinations of neutron-star masses up to the present are consistent with this value. We would not expect the neutron star in SN1987A to be much less massive.

The rapid pulse rate is not the only surprise in the detection of this pulsar. The pulse frequency varied in an approximately sinusoidal manner during the seven-hour observation. If this variation is interpreted as Doppler shift attributable to orbital motion, the companion must have a mass about the same as Jupiter ($0.001 M_{\odot}$) and its orbital radius would have placed it inside the pre-supernova star. Furthermore, despite repeated observations by the discoverers and others, the detection has not been confirmed. For the most sensitive of these observations, the limiting optical magnitude is about 21, 2–3 magnitudes (a factor of 10) fainter than the original detection. Nor have searches at radio, X-ray and γ -ray wavelengths been successful although, for various reasons, detection at these wavelengths is less likely than in the optical band.

The most probable explanation for this lack of confirmation is that the atmosphere surrounding the pulsar is only intermittently transparent. Although the outer parts of the supernova envelope have been optically thin for over a year now, we know very little about the central region. This may be much thicker and turbulent, resulting in rapid variations in the absorption and scattering along the path to the pulsar. It is difficult to understand, though, how the atmosphere could have been reasonably transparent for more than seven hours on 18 January but opaque before and since.

As is commonly the case in astronomy, there are other possible explanations for the observed phenomena that avoid the difficulties. If the object pulsed twice per spin (having a strong 'interpulse', as is observed for several short-period pulsars), the true rotation rate would be half the apparent value. But this is unlikely because Kristian *et al.* find no evidence for any signal at the sub-harmonic frequency of 984.315 Hz. More plausible, perhaps, is the suggestion made by Wang *et al.*⁶ (and others) that the pulsation is due not to the rotation of the star, but to a vibrational mode. Such modes have frequencies in the right range. Furthermore, they are likely to be damped on a timescale of the order of days by coupling with the rotation. This could explain the lack of confirmation. But the mechanism to excite the vibrations

and how these can generate pulses are not well understood, so new problems replace the old ones.

If the 2,000-Hz pulsation is due to vibration, why do we not also see the normal rotational pulsation? The most obvious reason is that we do not lie in the path swept out by the rotating beam or beams of the pulsar. For fast pulsars, the beamwidths are usually relatively wide, so that we have about a 50–50 chance of being in the beam if the rotation rate is more than 10 Hz or so. Probably more important is the effect of the rotation rate on the power of the rotating beam. Observations of other pulsars show that this is a strong function of the rotation rate and the strength of the pulsar magnetic field, especially in the optical band.

Decline

The continued decline of the supernova intensity shows that the rate of total energy loss from the pulsar is likely to be much less than that from the Crab pulsar. The exact limit is uncertain, because only a fraction of the energy loss may end up as electromagnetic radiation. Nevertheless, the indications are that either or both the rotation rate and the magnetic field strength are much less than for the Crab pulsar and hence that the pulsed luminosity is also much less. Given the distance to SN1987A, this would make the pulsar very difficult to detect.

A final explanation that must be considered is that the original detection of the 2,000-Hz pulsation was spurious. There is no doubt that the data taken by Kristian *et al.* on 18 January are strongly periodic. It is conceivable that this periodicity was generated in the equipment rather than being present in the light from the supernova. For several reasons, this seems unlikely. First, Kristian *et al.* have found no evidence for pulsations at this frequency in previous or subsequent observations with the same equipment. Second, the observed pulsations were very strong, many times stronger than the random fluctuations normally observed. Third, and most convincingly, the pulsations disappeared when the telescope was moved to another object at the conclusion of the supernova observations.

So, which ever way we look at it, the pulsar in SN1987A is a puzzle, a puzzle that is unlikely to be solved unless the pulsar is detected again. □

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