Pulsed Radio Sources

by
F. HOYLE
J. NARLIKAR
Institute of Theoretical Astronomy,
University of Cambridge

Pulses of energy may be emitted by collapsing supernovae in suitable circumstances.

THE recent discovery[1] of rapidly pulsed radio sources and the further detailed observations[2] of the source CP 1919+22 raise remarkable problems. Undoubtedly the theory which requires the least change in our concepts is that of a pulsating white dwarf. As long ago as 1952, Mestel[3] pointed out that nuclear fuel in the outer regions of a white dwarf can cause an explosive instability. There is therefore no difficulty in understanding how an oscillatory state might be set up. It is also possible that oscillations could be self-sustaining.

The first problem this theory has to face is that the oscillation period of CP 1919+22 is remarkably short—1·337 s. Periods of more than 10 s were rather to be expected[4]. Recently, however, Thorne and Ipser[5] have argued that fundamental periods as low as 3 s might well occur in some white dwarfs, and they remark that an overtone period as low as 0·2 s is possible. This lower limit is close to the period of 0·253 s reported in this issue of *Nature* by Pilkington *et al.* for the source CP 0950+08. It seems therefore that the theory of white dwarfs is just about able to accommodate the shortest period so far observed. The accommodation is, however, uncomfortably tight, particularly because the time constant of 0·1 s used in the first Cambridge survey would have prevented the discovery of appreciably shorter periods.

The second problem is that the radio pulse occupies only a small fraction of the cycle, only about 40 ms in 1·33 s for CP 1919+22. Moreover, the pulse rise is exceedingly steep—the rise time is <1 ms in this source. The disturbance leading to the radio pulse would have to be released at a sharply defined phase of each cycle and, to within a small margin, the same phase in every cycle. We could imagine a shock wave that reached the surface of the star always at a particularly defined phase, for example. The sharpness of the shock defines the steep rise of the pulse, while the pulse length is determined by the time difference between the arrival at the Earth of radiation from the centre of the disk and from the limb. Suppose the radiation from the centre of the disk arrives at time T. If R is the radius of the star, the radiation from the limb arrives at time $T+R/c$, thus giving a pulse length R/c. The pulse shape in the range $T \leq t \leq T+R/c$ can be determined in the following way. The radiation arriving at time t comes from the rim of a spherical cap of solid angle $2\pi(1-\cos\theta)$ where θ is the angle between the radius vector to the rim and the direction to the Earth. Clearly

$$t = T + (1-\cos\theta)R/c \qquad (1)$$

If the radiation is emitted isotropically, the amount received in time dt is proportional to

$$2\pi \sin\theta \, d\theta . \cos\theta \qquad (2)$$

where the factor $\cos\theta$ arises from projection of the area normal to the line of sight. From equations (1) and (2) we see that the pulse shape is given by

$$\mathcal{J}(t) = K . \left(T + \frac{R}{c} - t\right) \qquad (3)$$

where K is a constant. Thus a triangular pulse shape with a steep rise and linear fall is expected for isotropic emission.

The pulse length of CP 1919+22 is about 40 ms and requires $R \sim 1{\cdot}2 \times 10^9$ cm. This is too large to correspond to the short period models of Meltzer and Thorne[4]. The difficulty is resolved if we argue that the observation really represents a series of pulses each of shorter length. The published pulse shapes[2] suggest that this might be so. In the shock wave model, this would imply a series of shock waves occurring over ~ 40 ms in each cycle of CP 1919+22.

The third problem is to understand how such a precise timing of the pulses can be combined with the great fluctuations in their amplitudes. How can such a very regular phenomenon be consistent with large amplitude variations, even over as short a time as a few minutes ?

While these difficulties do not rule out the white dwarf explanation they make it reasonable to look for other explanations. One other possibility has recently been put forward by Saslaw, Faulkner and Strittmatter[6].

It is our chief concern in this communication to point out that a time constant of ~ 1 s follows from the collapse time of a supernova. According to previous ideas[8,9] a supernova is triggered by the endoergic nuclear reaction $^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n$ at the centre of an evolving massive star. The density and temperature at which collapse occurs have been calculated for various stellar masses. For masses in the range 10 $M_\odot$ to 30 $M_\odot$ the density was found to be $\sim 10^7$ g cm^{-3}. Because the implosion time is $[3\pi/32G\rho]^{1/2}$, this is $\sim 2/3$ s when we set $\rho = 10^7$ g cm^{-3}.

The fate of such a collapsing core has always been somewhat uncertain. Collapse into a gravitational singularity is one possibility, but it has always been thought more probable that the core will contrive to "bounce", in which case it will oscillate back to more or less the radius it had at the onset of collapse, about 10^9 cm. The time for a complete oscillation is essentially twice that estimated in the previous paragraph, namely, $\sim 4/3$ s, very close to the observed period of CP 1919+22, and close to 1·27 s for CP 0834+07 and to 1·19 s for CP 1133+17, but longer than the period 0·253 s of CP 0950+08. A shorter observed period, however, does not necessarily present a serious difficulty, because damping processes—for example, neutrino-emission—shorten the theoretical period.

At this stage we can follow one or other of two lines of development.

(*a*) The object continues to oscillate between a maximum radius $R_{\max} \sim 10^9$ cm and a minimum radius $R_{\min} \ll R_{\max}$. The value of $R_{\max}$ determines the pulse repetition rate, while the phase of $R_{\min}$—corresponding to the greatest compression of the object—determines the moment of pulse emission in relation to the cycle. The pulse could arise from the compression of a magnetic field, for example[7].

(*b*) The explosion of nuclear fuel in the outer regions of the star[8] reduces the total mass to less than the upper limit of a stable white dwarf. After the supernova explosion has taken place, the core then springs back to a white dwarf configuration.

Possibility (*a*) is new, while (*b*) connects with the white dwarf theory. It is not necessarily an objection to (*a*) that oscillations with $R_{\min} < R_{\max}$ would rapidly be damped—for example, by neutrino emission—because it is possible for the object to divide into a number of pieces which maintain constant high density, the oscillation being confined to the pieces—the pieces moving inwards together and outward together. Indeed, the theory of Saslaw, Faulkner and Strittmatter[6] can be incorporated into this possibility because it can be regarded as a case in which the core possesses appreciable angular momentum. In such a case it is possible for division to occur into two dense pieces in binary motion about each other.

The advantage of (*b*) in relation to the white dwarf, theory is that it provides a natural explanation of the periodicity of ~1 s. As we have already noted, periods of this order represent the shortest periods which it is possible for white dwarfs to have. Such stars are at the margin of stability. Increase the mass slightly and collapse occurs into the kind of object considered in (*a*). By working from above, however, by reducing the mass towards stability, we obtain an understanding of why the pulsed sources tend to lie near the margin of stability.

The dynamical energy in case (*a*) is $\sim 10^{54}$ ergs (ref. 7), enormous compared with the energy requirements of the pulsed sources, which amount to only $\sim 10^{28}$ ergs s^{-1}, at any rate so far as the radio emission is concerned. This would seem to us a disadvantage of (*a*) because we would expect such a large energy source would manifest itself in a much more dramatic form. On the other hand, it is perhaps easier to understand the rapid variations of shape and amplitude of the pulses in case (*a*). This is especially so if the object divides into a number of pieces. However well the pieces maintain an organized in-and-out motion, we cannot expect the detailed arrangement of the pieces to be exactly the same at minimum radius, $R_{\min} \ll R_{\max}$, in each cycle. Variations over a few cycles or even from cycle to cycle might be expected and could provide the explanation of the remarkable changes of amplitude of the radio pulses.

Next we remark on the likely composition of the white dwarf corresponding to case (*b*). Hoyle and Fowler[8] considered that most of the helium produced by $^{56}\mathrm{Fe} \rightarrow 13\alpha + 4n$ did not recombine. On this view, the white dwarf would be largely helium, as suggested by Thorne and Ipser[5]. Some helium would combine to form $^{12}\mathrm{C}$ and higher elements, however, while the free neutrons would eventually decay to protons. It is interesting that $^{12}\mathrm{C}(p,\gamma)^{13}\mathrm{N}(\beta^+)^{13}\mathrm{C}$ provides a source of $^{13}\mathrm{C}$. Together with the α particles, $^{13}\mathrm{C}$ has the very temperature sensitive reaction, $^{13}\mathrm{C}(\alpha,n)^{16}\mathrm{C}$. This reaction has been considered as a source of instability in stars. The possibility suggests itself that this same reaction might be the source of white dwarf oscillations.

Finally, we note that an active lifetime of at least 3×10^6 years is necessary for the supernova residue in both cases (*a*) and (*b*). In 3×10^6 years we expect about 10^5 supernovae to occur of which ~10 would lie within 100 pc. This is of the order of the density of pulsed sources suggested by the Cambridge survey. Because there are $\sim 10^{14}$ cycles in 3×10^6 years, it is therefore necessary that the secular change of period per period should not be more than about one part in 10^{14}. This indeed seems to be the case (F. G. Smith, private communication).

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Linear Polarization in Pulsating Radio Sources

by

A. G. LYNE

F. G. SMITH

University of Manchester,
Nuffield Radio Astronomy Laboratories,
Jodrell Bank

Signals from all the known radio sources are linearly polarized. The pulses often seem to be made up of separate components showing a high degree of polarization.

THE mechanism of emission from the pulsating radio sources reported by Hewish *et al.*[1] seems to be quite different from that of any other celestial radio source, particularly because of the wide frequency band over which intense radiation is emitted simultaneously[2]. An analogy may be found, however, in the radio pulse emitted by a cosmic ray shower[3,4], in which a sheet of particles moving relativistically may emit linearly polarized radiation when they are deflected by the Earth's magnetic field. It seemed appropriate therefore to search for linear polarization in the pulsating stars, and we here report the successful detection of linear polarization in all of the four known sources.

Initial tests on the first source *CP* 1919 at $\alpha = 19^h\ 19^m$ $\delta = 21°\ 47'$ were disappointing. Two orthogonal dipoles in the Mark I radio telescope were connected to separate receivers at 408 MHz, and the strength of the recorded pulse averaged over 1 min was compared in the two receiver channels. No significant difference was found, although observations were made at several different position angles. It was realized, however, that the variable amplitude of the pulse might be confusing the observations, and that the complex structure of the pulse might imply different origins for different parts of the pulses so that polarization would only be observed during the rare occasions when individual pulses are strong enough for the structure to be resolved in some detail.

The pulses from the source, at $\alpha = 09^h\ 50^m$, $\delta = 8°\ 4'$, are usually stronger and simpler, and seem to have fewer separate components. A recording of individual pulses from this source immediately showed a very high degree of linear polarization. Fast galvanometer recordings of

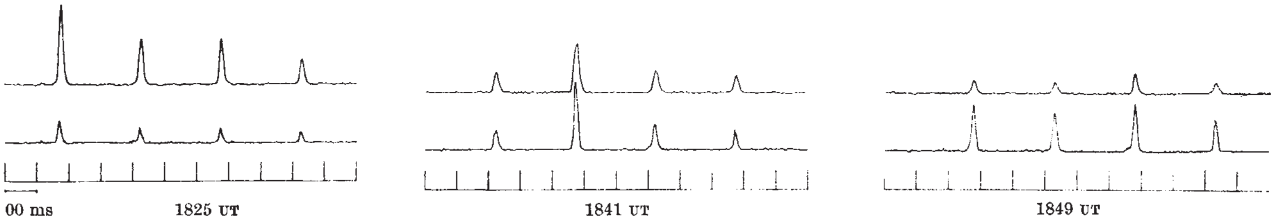

Fig. 1. Fast galvanometer recordings of the outputs of two receivers at 151 MHz connected to orthogonal dipoles at the focus of the Mark I telescope. These were made on the source at $\alpha = 09^h\ 50^m$, $\delta = 8°\ 15'$ on April 1, 1968. The change of relative amplitudes in the two channels indicates a linear polarization in these pulses.