7.3 PHYSICAL PROCESSES AND PARAMETERS IN THE MAGNETOSPHERE OF NP 0532

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Abstract. The Crab Nebula pulsar conforms to the model of a rotating magnetised neutron star in the rate of energy generation and the exponent of the rotation law.

It is suggested that the main pulse is due to electrons and the precursor to protons. Both must radiate in coherent bunches. Optical and X-ray radiation is by the synchrotron process.

The wisps observed in the Nebula may represent the release of an instability storing about 10^{43} erg and 10^{47-48} particles.

Finally, some considerations are made about the general relation between supernova remnants and rotating neutron stars.

1. Introduction

It is well known that the discovery of NP 0532 inside the Crab Nebula has played a decisive role in our understanding of the pulsar phenomenon.

This is the source with the shortest observed period (about 33 msec), compatible only with the idea that pulsars are related to rotating neutron stars (Gold, 1968).

The lengthening of its period corresponds to a loss of rotational energy close to 10^{38} erg sec^{-1}, about the same as the total luminosity of the entire Crab Nebula. As noted by several authors, this confirms the suggestion of an electrodynamic link between the rotation of neutron stars and the activity in supernova remnants (Pacini, 1967, 1968).

NP 0532 is the only pulsar known at present to be not only a radio source but also a strong emitter of infrared, optical, X-ray and, perhaps, gamma-ray radiation. The ratio between the high frequency emission (about 10^{35}–10^{36} erg sec^{-1}) and the radio output (about 10^{31} erg sec^{-1}) is such that one could almost call NP 0532 a radio-quiet pulsar. The pulses themselves account only for about one percent of the total release of rotational energy: they represent only a minor energy loss in the neutron star magnetosphere, probably by the same particles which are continuously injected into the Crab Nebula.

In the following, we consider some processes which are likely to be important in the magnetosphere of a rotating neutron star and a model for pulsar radiation. In Section 1 we review the electrodynamics of rotating neutron stars. In Section 2 we discuss the electromagnetic spectrum of NP 0532 and we connect the information obtained from this radiation with the more general pulsar electrodynamics. In Section 3 we present a tentative scheme for the origin of the wisps in the Crab Nebula. Finally, in Section 4, we discuss some aspects of the evolution of supernova remnants in relation to the evolution of rotating neutron stars.

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Davies and Smith (eds.), The Crab Nebula, 394–406.

https://doi.org/10.1017/S0074180900007749 Published online by Cambridge University Press

2. Electrodynamics of Rotating Neutron Stars

Fast rotation and very strong magnetic fields are expected in a newly born neutron star. For illustrative purposes we consider a pre-supernova star with a radius $R \sim 10^{11}$ cm, angular rotation frequency $\Omega \sim 10^{-6}$ sec (rotation period $P \sim$ months), magnetic fields ranging between a few and, say, 10^4 G. If this star collapses to a typical neutron star radius $\sim 10^6$ cm, approximate conservation of angular momentum would lead to $\Omega \sim 10^4$ sec^{-1} and periods in the milliseconds range. Because of the very great electrical conductivity, the magnetic field also increases and leads to $B_0 \sim 10^{10}$–10^{14} G (Ginzburg, 1964, Woltjer, 1964). Note that the virial theorem applied to neutron stars sets the upper limits $\Omega \lesssim 10^4$ sec^{-1} and $B_0 \lesssim 10^{17}$ G*.

The interaction between the neutron star and the surrounding medium should therefore be dominated by fast rotation, strong magnetic fields and strong induced electric fields. The existence of the pulsar phenomenon suggests that the magnetic field is not symmetric with respect to the rotation axis (oblique rotator model).

Several features of the neutron star magnetosphere have been discussed and we shall consider only the most important points. More details are contained in the original papers and in some review articles (see, e.g., Cavaliere, 1969).

As first noted by Gold (1968), the neutron star can be surrounded by a corotating magnetosphere up to the speed of light distance $r_{cr} \sim c/\Omega$, provided that the magnetic energy exceeds the plasma energy up to this critical point. If the field is not sufficiently strong, corotation can be enforced only up to the 'speed of Alfvén distance' $r \sim v_A/\Omega$ (v_A is the Alfvén velocity).

Goldreich and Julian (1969) and Michel (1969) have shown that the neutron star should be surrounded by a dense plasma since the induced electric fields continuously extract charged particles from the surface of the star.

One can divide the near magnetosphere ($r < c/\Omega$) in two different parts. The particles attached to the field lines which do not cross the speed of light cylinder form the corotating magnetosphere. Near the star, the particles probably have an energy close to the escape energy (say, 10 up to about 100 MeV for protons). If however they move close to the critical distance, they should be relativistic.

The field lines which pass through the speed of light cylinder are open and the particles can stream out along them. As discussed by Goldreich and Keeley (1970), they can be accelerated by a component of the electric field parallel to the magnetic lines. The efficiency of this acceleration is uncertain because the plasma can partially neutralize the induced electric field. In the absence of space charges and radiation losses the Crab pulsar could inject particles with an energy up to about 10^{16} eV, but in real life the energies attained are likely to be much less than this upper limit. Since the mechanism is of electrostatic nature, protons and electrons would reach the same energy, unless radiation losses drastically modify this situation. We also recall that

* If $B_0 > 4 \times 10^{13}$ G one should however also take into account quantum effects (see, e.g., Chiu and Canuto, 1970a).

the protons and electrons move preferentially along different field lines (Goldreich and Julian, 1969).

The gyration around the magnetic lines cannot be excited simply by the accelerating forces since they act adiabatically on the gyration time scale. We speculate that a gyration will arise either because of collisions or because of transverse electric fields. Our picture for the motion of the particles includes a component along the field lines and a simultaneous gyration around them: we shall return to the consequences of this picture for the pulsar radiation in the next section.

In the case of an oblique rotator, retardation effects modify the electromagnetic field close to the critical distance: the neutron star radiates magnetic dipole radiation at the basic frequency Ω (Pacini, 1967, 1968; Ostriker and Gunn, 1969). The lines of force are swept back and the resulting tension corresponds to a torque slowing down the star. Under the assumption $B^2/8\pi > nmc^2\gamma$ (n is the plasma density) the effect of the outflowing plasma results in a similar (but quantitatively less important) torque. Apart from geometrical factors, the energy radiated is given by

$$L \sim \frac{B^2}{8\pi} c 4\pi \left(\frac{c}{\Omega}\right)^2 \tag{1}$$

where $B = B(r_{cr})$. In a dipole field

$$L \sim \frac{1}{2c^3} B_0^2 a^6 \Omega^4 \tag{1'}$$

(B_0 is the surface field, a is the stellar radius).

An exact treatment of the problem (Deutsch, 1955) confirms this intuitive result but gives a numerical factor $\frac{2}{3}$ instead of $\frac{1}{2}$.

The loss of rotational energy corresponds to a slowing down law $\dot{\Omega} \propto \Omega^n$ where $n = 3$. The laws $L \propto \Omega^4$ and $\dot{\Omega} \propto \Omega^3$ imply a strictly dipolar geometry $B(r) \propto r^{-3}$, as one can immediately see from our simple derivation. In real life it might be necessary to take into account the plasma in the magnetosphere: the outflowing particles will tend to stretch the lines of force in a radial direction. For a purely radial field $B \propto r^{-2}$, one finds (with different coefficients) $L \propto \Omega^2$ and $\dot{\Omega} \propto \Omega$.

For the Crab pulsar, before the well known speed-up, the observed value was $n \sim 2.2$ (Richards *et al.*, 1970), thus suggesting a dipole field slightly perturbed by the plasma. The rate of slowing down tells us (under the assumption of an electromagnetic torque) the strength of the magnetic field on the star. For most pulsars, the resulting value is around 10^{12} gauss, in agreement with the expectations.

In the far magnetosphere ($r > c/\Omega$) the magnetic field develops a toroidal component and is given by

$$B(r) = \frac{B_0 a^3}{c^2} \frac{\Omega^2}{r}. \tag{2}$$

For the Crab Nebula, $\Omega \sim 200\ \text{sec}^{-1}$, $B_0 \sim 3 \times 10^{12}$ G, $r \sim 10^{18}$ cm: the resulting strength $B \sim 10^{-4}$ G matches the estimated value and suggests that also the nebular field is generated by the pulsar.

The particles escaping from the near magnetosphere can be accelerated further in the far wave region by the magnetic dipole radiation (Ostriker and Gunn, 1969). The mechanism is very efficient if the particles and the fields move in phase. For NP 0532, at $r \sim 10^8$ cm, $E = B = 10^6$ G and the particles can reach top energies around 10^{14} eV. A relatively dense plasma would however reduce the number of particles able to reach the maximum energy: the presence of such plasma appears unquestionable on several grounds.

First, its existence is suggested by the lowering of the slowing down index with respect to the pure dipole case. Second, an integration of the Crab Nebula injection spectrum (see, e.g., Shklovskii, 1969) corresponds to an outflow of about 10^{40} particles sec^{-1}. At the critical distance the density should therefore be $n \sim 10^{12}/\varepsilon$ cm^{-3} (ε is a geometrical factor introduced to take into account the possibility of an anisotropic injection). Finally, as we shall see in the next Section, a density between 10^{12} and 10^{14} cm^{-3} is indicated by the pulsar radiation. A description of the far wave acceleration based upon a quasi-vacuum approximation is therefore probably too optimistic.

Magnetic dipole radiation can accelerate particles but only a few of them probably reach the top energy $\sim 10^{14}$ eV. This would agree with the small proportion of very energetic electrons present in the Crab Nebula. As noted by Woltjer (1969), it is impossible to explain the spectrum of the Crab Nebula with a monochromatic injection of relatively few very high energy electrons which are then decelerated by radiation losses: the number of particles with energy $\lesssim 10^9$ eV exceeds in the nebula that of particles with energies $\gtrsim 10^{13}$ eV by a factor $\sim 10^6$. One should instead require an injection with widely different energies, roughly between 10^8 and 10^{14} eV. Both the near and the far field acceleration are likely to determine the injection spectrum.

Finally, we make a brief comment about the rapid decline of injection at energies less than about 100 MeV (see, e.g., Shklovskii, 1969). The cut-off occurs around the escape energy of protons from the neutron star and this might be more than a pure coincidence. In an electrostatic mechanism protons and electrons would acquire the same energy: if the electric field value is set by the protons and one can neglect deceleration effects one expects that also the electrons will have a minimum energy around 100 MeV.

3. The Electromagnetic Spectrum of NP 0532

The pulses could, in principle, provide some direct information about the neutron star magnetosphere. Their origin is however controversial and no general agreement exists on whether they are emitted close to the surface or whether they arise in a region distant about c/Ω from the star. The only obvious point is that they should come from a region where the magnetic energy density is not overcome by the plasma energy density: otherwise it would be difficult to imagine a well defined radiating sector of the magnetosphere.

Also, the very high brightness temperature of the radio emission implies a very coherent radiation mechanism. Different proposals have been investigated, such as coherent plasma effects (see, e.g., Ginzburg *et al.*, 1969), maser effects (Chiu and Canuto, 1970b), correlated motion of bunches of charges (Gold, 1968; Bertotti *et al.*, 1969; Komesaroff, 1970; Goldreich and Keeley, 1970; Pacini and Rees, 1970). As several authors have recognized, the incoherent high frequency emission from NP 0532 can instead be due to the usual synchrotron process: the small duty cycle $\delta \sim 10^{-2}$ of the pulsar demands an equally well collimated distribution of pitch angles for the motion of the particles around the field lines (Pacini and Rees, 1970).

It is often claimed that the pulsed nature of the source implies an emission within a few stellar radii, where the open field lines subtend a small angular sector. It is not clear to us whether this claim (at least when made a priori) is really justified. The distribution of the magnetic field close to the star can be much more irregular than a simple dipole. Also, it might be difficult to achieve a well collimated distribution of pitch angles close to the star since the expected very high plasma density could lead to collisions and smear out the collimation.

On the other hand the far wave solution of the stellar electromagnetic field clearly shows a regular, large scale structure (Deutsch, 1955). Because of the lower density, the collisions would not influence the distribution of pitch angles: a small pitch angle could perhaps result from adiabatic invariance. We shall therefore concentrate upon a model where the pulses are generated close to the critical distance and the radiation processes are related to the motion of those particles which move away from the star along the open field lines. At the end of this section, we shall also indicate some parameters which would apply if the pulses were generated within a few star's radii. Our treatment will follow the one given in earlier papers (Bertotti *et al.*, 1969; Pacini and Rees, 1970) with minor modifications and additions.

We have previously noted that the motion of particles in the open magnetosphere should probably involve two components: one component along the lines of force and a gyration around them. Since the field lines have an intrinsic curvature, the motion along them gives rise to a radiation process different from the synchrotron radiation resulting from the gyration. The two radiation processes are independent, since the Larmor radius is much smaller than the radius of curvature of the field lines.

We investigate first the generation of incoherent synchrotron radiation. At $r \sim c/\Omega \sim 10^8$ cm the strength of the magnetic field has dropped to about 10^6 G. The small duty cycle $\delta \sim 10^{-2}$ implies for the pitch angle $\Psi \lesssim 5 \times 10^{-2}$ rad; the corresponding upper limit for the perpendicular component of the magnetic field is $B_\perp \lesssim 5 \times 10^4$ G.

In a field of this order, the observed emission between the infrared and the X-ray frequencies demands a distribution of electron energies roughly between 10^8 and some 10^{10} eV. If the recent report (Vasseur *et al.*, 1970) of a gamma-ray emission will be confirmed, some electrons should have an energy $\gtrsim 10^{11}$ eV. The emitting volume is uncertain but the duty cycle again implies that only a fraction $\sim 10^{-2}$ of the speed of light circumference (about 10^9 cm) is involved in the radiation. If we assume an emitting volume $V \sim 10^{21}$ cm^3, the observed output requires an electron density close to 10^{12} cm^{-3}.

The usual lifetime of the electrons against radiation losses is small but irrelevant: while they radiate, the electrons are also accelerated by the electric fields. The energy gains can largely exceed the losses and the particles escape beyond the critical distance.

Two different explanations for the low frequency cut-off at $\nu < 8 \times 10^{14}$ Hz appear possible. O'Dell and Sartori, (1970) have noted that synchrotron radiation with small pitch angle Ψ has a turnover at a frequency $\nu \sim 10^6\ B/\sin\Psi$. At lower frequencies the emission is due to the cyclotron process and declines steeply. With our previous parameters one would predict a cut-off at $\nu \sim 2 \times 10^{13}$ Hz but a smaller pitch angle would fit the observations.

On the other hand, Shklovskii (1970) has considered the possibility of synchrotron reabsorption: fields of the right order of magnitude ($B_\perp \sim 10^3$–10^4 G) are implied by the observations.

The possible extreme range of values $3 \times 10^3 \lesssim B_\perp \lesssim 5 \times 10^4$ G corresponds to a small uncertainty in the energy of the particles (roughly, $\gamma \propto B_\perp^{-1/2}$) but to a somewhat larger uncertainty in the plasma density (roughly, $10^{12} \lesssim n \lesssim 10^{14}$ cm^{-3}).

Despite this uncertainty, there is a very good agreement between the parameters inferred from the pulsar radiation and the requirements stemming from the link between the neutron star and the Crab Nebula. As pointed out in the previous section, a flux $\sim 10^{40}$ particles sec^{-1} across the speed of light distance gives there a density $n \sim 10^{12}/\varepsilon$ cm^{-3}. If the injection is isotropic $\varepsilon = 1$; if it only occurs along the field lines responsible for the pulsar radiation, $\varepsilon \sim 10^{-2}$.

The presence at $r \sim 10^8$ cm of particles with energies up to 10^{10}–10^{11} eV implies an acceleration mechanism in the near magnetosphere, such as the one suggested by Goldreich and Keeley (1970). Additional acceleration in the far field by magnetic dipole radiation can account for the presence in the Crab Nebula of some particles with energies up to about 10^{14} eV.

With the above parameters, the magnetic energy exceeds the plasma energy: the torque slowing down the star is therefore mostly electromagnetic. The outflowing, relatively dense, plasma can however partially stretch the field lines in a radial direction and account for a slowing down index less than 3.

Since the peak of synchrotron radiation is proportional to $B(r_{cr}) \propto P^{-3}$, slow pulsars should emit by this mechanism at infrared frequencies, rather than in the optical or X-ray band. The power radiated is $\propto nV\gamma^2 B^2$ (V is again the emitting volume): the dependency from the magnetic field implies a synchrotron luminosity $\propto P^{-6}$ but a stronger dependency should be expected since the acceleration of particles by slow pulsars is probably less efficient than in the Crab. Also, the synchrotron luminosity of NP 0532 should decrease by a quantity $\gtrsim 0.01$ magnitudes per year.

We consider next the origin of the coherent radio emission which we ascribe to the component of motion along the field lines. At a distance r from the star, the radius of curvature of these lines is $\varrho \sim (r\, c/\Omega)^{1/2}$ (see, e.g., Goldreich and Keeley, 1970). Close to the critical distance $\varrho \sim c/\Omega$ and therefore there is no difference between considering the radiation as due to the curvature of the field lines or to a general "corotation" at the basic frequency Ω.

Radio frequencies up to $\nu_{cr} \sim 10^8$–10^9 Hz will arise if the Lorentz factor $\gamma_{\parallel}$ corresponding to the parallel component of motion satisfies the relation

$$\frac{1}{2\pi}\frac{c}{\varrho}\gamma_{\parallel}^3 \gtrsim \nu_{cr}\,. \tag{3}$$

For NP 0532 this gives, roughly, $\gamma_{\parallel} \gtrsim 10^2$. A similar value $\gamma > \delta^{-1} \sim 10^2$ can be independently inferred from the requirement that the duty cycle is a consequence of the existence of an active sector of the magnetosphere and is not limited by the emission cone of the individual particles (otherwise the duty cycle would change with the frequency in a known way).

The brightness temperature of NP 0532 in the radio band is close to 10^{26} K but occasionally very strong pulses are observed with $T_b \sim 10^{30}$ K. This very high degree of coherence can arise because of strong correlations in the motion of particles and from the formation of charged bunches. The brightness temperature is limited by thermodynamics

$$kT_b \lesssim (\text{energy per bunch})\,. \tag{4}$$

An upper limit to the size of the bunches is given by the wavelength of the emitted radiation, say ~ 1 up to about 10^2 cm. Note however that this limit refers only to the size along the visual line: in principle, the other sizes could be larger. The radio spectrum should largely reflect the degree of coherence at a given wavelength (i.e. the spectrum of correlations in the plasma), rather than the distribution of particle energies.

Since Relations (3) and (4) are only inequalities and we don't know the sizes of the bunches different from the one along the line of sight, the number of particles taking part in the radio emission cannot be reliably estimated. A priori, one can however expect that it will turn out to be smaller than the number of particles inferred from the optical and X-ray emission. First, only a small part of the particles responsible for the incoherent radiation is likely to have a sufficiently small pitch angle to give also $\gamma_{\parallel} \gtrsim 10^2$. Second, it is likely that there will be a partial neutralization inside the bunches: this would reduce the efficiency at which the bunches radiate coherently without affecting the incoherent emission.

With these uncertainties in mind, we examine for illustrative purposes two extreme cases.

We first consider quasi-spherical bunches with volume $L^3 \sim \lambda^3 \sim 10^2$ cm^3; also, we assume that the density and the energy of the plasma is close to the limits $n \sim 10^{12}$ cm^{-3} and $\gamma_{\parallel} \sim 10^2$. The number of particles per bunch is $\sim 10^{14}$ and the energy per bunch $\gtrsim 10^{10}$ erg. The upper limit to the brightness temperature is $\sim 10^{26}$ K. Note that the

https://doi.org/10.1017/S0074180900007749 Published online by Cambridge University Press

energy of the particles largely exceeds the electrostatic energy (about 10^6 erg): the formation of these bunches does not pose energetic problems.

The motion along the curved field lines causes a radiation per unit frequency (close to $\nu_{cr} \sim 10^8$ Hz)

$$p_\nu \sim \frac{e^2}{c} \frac{c}{\varrho} \gamma_{\|} nV(nL^3). \tag{5}$$

The previous parameters can therefore easily account for the emitted power of NP 0532 (radio output $\sim 10^{31}$ ergs over a band $\sim 10^8$–10^9 Hz).

Alternatively, we can assume an 'effective density' $n = n_p - n_e \sim 10^7$ cm^{-3} which is of the same order as the density of space charge inferred at $r \sim c/\Omega$ by Goldreich and Julian (1969). This value does not contradict a total density $n_p \simeq n_e \simeq 10^{12}$–$10^{14}$ cm^{-3} since it only refers to the net charge and, furthermore, only to the large scale distribution. We keep $\gamma_{\|} \sim 10^2$ (which is likely to be an underestimate). One finds then that the volume of the bunches should be around 10^{13} cm^3. Since the size cannot exceed the emitted wavelength, the bunches would be very elongated in a direction transverse to the line of sight.

Intermediate parameters are possible and the uncertainty in the number of particles involved in the radio emission is very large. Fortunately, in the case of NP 0532, the incoherent radiation does not suffer the same uncertainty and can be used to give a reliable estimate of the plasma parameters.

The optical pulses should be somewhat broader than the radio pulses (because of the additional contribution of the pitch angles): this agrees with the observations.

An interesting aspect of the radio emission is the occasional presence of very strong radio pulses: probably they arise when richer bunches are formed, which is energetically possible. Also, the main radio pulse is preceded by a precursor absent at optical and X-ray frequencies. We have already recalled in Section 2 that protons move along field lines different from those followed by electrons.* It seems therefore possible to account for the precursor in terms of radiation from the proton field lines. The protons could radiate at radio frequencies provided that they satisfy Equation (3) but they would be absent at optical and X-ray frequencies since proton synchrotron radiation would be negligible. It is interesting that the precursor shows much more linear polarization than the main pulse. This agrees with the picture since the radio emission is strongly polarized only when it falls at (or above) the critical frequency. If $\gamma_{\|}$ (protons) $\sim 10^2 \ll \gamma_{\|}$ (electrons) (as one should expect from an electrostatic mechanism) the protons would radiate close to the critical frequency and their emission would be very polarized. The electrons would instead be observed before the critical frequency, where the output can be magnified by coherence but the polarization would be small. Slow pulsars might be unable to reach $\gamma_{\|}$ (protons) $\sim 10^2$ if the efficiency of acceleration decreases with time: this agrees with the absence of a similar precursor in their emission.

* This statement should be interpreted in the sense that field lines at different latitudes have space charges of different sign and not in the sense that each field line carries one sign of particles.

Concerning the interpulse, probably it is emitted at the opposite side of the star: the time delay between the main pulse and the interpulse represents the difference in the light travel time.

Finally, we make some comments about the alternative scheme of an emission (by the same processes) close to the star. More details can be found in previous papers (Komesaroff, 1970; Pacini and Rees, 1970). The main point is that the low-frequency cut-off in the incoherent radiation can be neither cyclotron turn-over nor electron synchrotron reabsorbtion. The very high magnetic fields close to the star would imply a cut-off at frequencies much higher than observed. The only possibility of which we are aware (Pacini and Rees, 1970) is that the radiation could be due to protons instead of electrons. In this case the turn-over can be explained by synchrotron reabsorbtion in a field $B_{\perp} \sim 10^9$ G. The model requires a very high plasma energy density close to the star and the acceleration of relativistic particles should be essentially limited to the star's surroundings. Furthermore, the plasma energy exceeds the magnetic energy well before the critical distance. The torque slowing down the star would be due to the plasma and much of the electrodynamics discussed so far would be irrelevant.

In our opinion, the main problem with this alternative scheme (valid at least as long as no other explanation for the cut-off at $\nu \lesssim 8 \times 10^{14}$ Hz is available) is that it seems very unlikely that we can see only proton and no electron radiation. It seems to us that an emission close to the speed of light distance (either a bit inside or a few basic wavelengths c/Ω outside) is strongly supported by

(1) the agreement between the plasma density estimated from the radiation and the required output in the Crab Nebula of about 10^{40} electrons sec^{-1}.

(2) the explanation of the cut-off at $\nu < 8 \times 10^{14}$ requiring fields $B_{\perp} \sim 3 \times 10^3 - 5 \times \times 10^4$ G.

(3) the expected very small synchrotron power from slow pulsars.

(4) the interpretation of the precursor in terms of proton emission.

4. The Origin of the Wisps in the Crab Nebula

We present in this section some preliminary considerations about the origin of the wisps in the Crab Nebula. These bright features, discovered many years ago by Baade, have been recently investigated in great detail by Scargle (1969). They have a semi-periodical recurrence of activity, about once or twice per year, and involve the sudden release of about $10^{43 \pm 1}$ ergs from the center of activity in the Crab Nebula.

There is some evidence (Scargle and Harlan, 1970) that the wisps became active in the first weeks after the speed-up of NP 0532, thus suggesting a relation between the two phenomena. We accept, for the time being, this evidence which clearly awaits confirmation from future events.

The increase in rotational energy of the neutron star during the speed-up was around 10^{41} erg, clearly insufficient to explain the energetics of the wisps. Also, the change in the pulsar period $\Delta p/p \sim 2.5 \times 10^{-9}$ would produce only a very small change in the flux of energy from the neutron star. It is therefore worth investigating some other possibilities for the connection between the wisps and the speed-up.

The energetics of the wisps roughly matches instead the energy content of the near magnetosphere of NP 0532, since $B_0^2 a^3 \sim 10^{43}$ erg. One should therefore consider the possibility that the wisps arise, from time to time, because of a sudden instability releasing an amount of plasma energy comparable to the energy in the near magnetosphere.

As seen before, the particles moving along the open field lines gain much energy and escape continuously from above the magnetic poles; they give rise to the pulsar radiation and to a steady input of relativistic particles in the Crab Nebula. The situation is different in the corotating magnetosphere, around the rotation axis. Here the particles can accumulate and, close to the star, their individual energy is probably between 10 and, say, 100 MeV. Much of the magnetic energy is stored close to the star and can confine the particles up to the point when the magnetic and the plasma energies are of the same order. The total number of particles which can be confined is around 10^{47}–10^{48}, with a total mass $M \sim 10^{-9}$–$10^{-10} M_{\odot}$. When the limiting value has been reached, the system could explode and release the particles into the Crab Nebula.

One can evaluate the time interval between two successive events. The corotating magnetosphere is probably fed at about the same rate as the open magnetosphere, that is about 10^{40} particles sec^{-1} are injected into it. The time necessary to reach the critical value is therefore between several months and one year, in agreement with the frequency of the wisps.

The presence of a dense plasma can indirectly affect the continuous slowing down of NP 0532 by deforming the structure of the field in the near magnetosphere. This effect adds itself to the previously mentioned effect of the outflowing plasma. One expects that after the flare the magnetosphere will be less perturbed (until replenished again) and that the field be closer to a dipole. There is indeed some evidence that the slowing down index n became after the speed-up closer to the dipolar value $n = 3$ (Drake, private communication).

A few days after the explosion, the plasma would have reached a distance $\sim 10^{15}$–10^{16} cm and one could observe a small increase in the pulsar dispersion measure. The rate of increase and its actual value are uncertain because they depend upon the expansion geometry and the plasma energy (a purely relativistic gas would clearly be less dispersive than a thermal gas); a tentative value is around $10^{16 \pm 1}$ electrons cm^{-2}. It is interesting that an increase of the dispersion measure was actually observed at Arecibo by Rankin and Roberts (private communication).

If the release of plasma is sufficiently well collimated with the rotation axis, and does not change appreciably the angular momentum of the star, the mass change in the corotating system 'star-magnetosphere' leads to a speed-up

$$\frac{\Delta\Omega}{\Omega} \sim \frac{\Delta M}{M} \sim 10^{-9}\text{–}10^{-10}. \tag{6}$$

It seems therefore possible to account for the observed increase in the pulsar frequency as a by-product of the same instability giving rise to the wisps.

Finally, the presence of a sinusoidal oscillation with period $P=77\pm7$ days was reported before the glitch (Richards *et al.*, 1970) but seems to have disappeared since (Duthie and Murdin, 1970). This would rule out an interpretation based upon planetary perturbations or mechanical precessions connected with the neutron star structure. It will be worth exploring an alternative explanation based upon the interaction between the skew stellar field and the axial field which would set up in the corotating magnetosphere. The disappearance of the plasma in the corotating magnotosphere for some time after the flare could account for the disappearance of the oscillations. One could expect that the oscillations will set in again in the coming months and that they represent a warning signal before a new glitch and wisp activity.

5. The Crab Nebula and the Other Supernova Remnants

We conclude with some general remarks about the relation between the activity and the morphology of supernova remnants and the evolution of the central neutron star.

It has become clear since the discovery of NP 0532 that the activity in the Crab Nebula follows the generation of high energy particles and of a relatively strong large scale magnetic field by the central neutron star. The Crab Nebula is however usually regarded as an 'unique' object: many other remnants show much less activity and are associated with a shell-structure, rather than a diffuse structure (see, e.g., Cas A).

This difference might stem from the absence in the other remnants of a neutron star and the present theory of supernova explosions is unable to predict the probability of finding a neutron star in a given SN remnant. Also, some attempt to find a bright pulsar in Cas A and other remnants have apparently failed.

On the other hand, both Cas A and the Tycho source SN 1572 are associated with an X-ray emission (see, e.g., Gorenstein, 1970). The spectral information is still insufficient to decide whether this radiation is non-thermal or whether it results from bremsstrahlung. If however the emission is due to the synchrotron mechanism, then there is the need for continuous injection of relativistic electrons, probably related to the presence of a rotating neutron star.

What kind of pulsars could one expect in these remnants? Also, why do they show a shell-like structure, rather than a diffuse structure like the Crab Nebula?

A possible answer to these questions has been given before (Cavaliere and Pacini, 1970; Pacini, 1970) and we recall here the arguments.

If the loss of rotational energy gives rise to the steady luminosity L of the remnant (like in the Crab Nebula), we have

$$L=\frac{2}{3c^3}B_0^2a^6\Omega^4\,. \tag{7}$$

Also, a neutron star with magnetic field B_0 and age t has a period P

$$P^2(t) = P_0^2 + 2 \times 10^{-39} B_0^2 t \quad \text{(sec., G)} \tag{8}$$

where P_0 is the initial period and the numerical coefficients refer to a standard neutron star.

Under the assumption $P \gg P_0$, the previous equations determine the period and the magnetic field of the neutron star on the basis of the known age and total luminosity of the remnant. Both for Cas A and Tycho one finds 0.5 ± 0.3 sec and magnetic fields around 10^{14} G.

The relatively long period does not contradict the known ages (a few hundred years) since the very strong magnetic field causes a rapid slowing down. Note that the injection rate in Cas A changes by about 1% a year, in agreement with the observed decrease of the radio emission (usually ascribed to expansion losses).

Slow pulsars inside these remnants would be difficult to detect because of the weak radio emission (say, for analogy with other slow pulsars, 10^{28}–10^{30} erg sec^{-1}), but it seems extremely important to search for them and lower the present limits.* Because of the long period and the arguments given in Section 2, no pulsed optical or X-ray radiation should be expected.

The shell structure itself of these remnants could be related to the presence of a long period source. One can see from Equation (2) that a slowly rotating neutron star can generate only a weak extended field. Even if the central object produces relativistic particles, they will not radiate very strongly over most of the volume occupied by the remnant. Most of the emission would arise in the outer shell: here the magnetic field is not directly connected with the pulsar and can be stronger because of compression.

If the above point of view is correct, then one should conclude that the most important parameter determining the evolution of a SN remnant is the magnetic field strength on the surface of the central neutron star. Also, the apparently exceptional character of the Crab Nebula appears to be simply a consequence of the fact that, with a surface field around 10^{12} G, the central star can remain a long lasting producer of a relatively strong nebular field and high energy particles.

Finally, some neutron stars could be born with fields much less than 10^{12} G, say around 10^{10} G. In this case, as we have shown before (Pacini, 1970), the central neutron star would still have a period in the range ~ 10 msec after several million years, that is long after the SN remnant has disappeared. Since fast pulsars are probably associated with strong optical and X-ray emission, some of the existing X-ray sources could be old, but still very fast, pulsars.

We would not be surprised if it will turn out in the future that our present knowledge of the pulsar phenomenon is very incomplete, having missed slow pulsars in

* According to a private communication from Dr. A. Hewish (December 1969) the Cambridge search can put a limit for Cas A (pulsed flux) $\lesssim 1\%$ (total flux). Note that not even a pulsar like NP 0532 would have been detected against the strong nebular background.

some young shell-like SN remnants and old but fast rotating neutron stars hidden among some X-ray sources.

Acknowledgements

This work was supported partly by NSF under Grant GP-9621 and partly by the Office of Naval Research under contract N-00014-67-A-0077-0007. We are especially indebted to Drs. A. Cavaliere and M. Rees for useful discussions.

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