NEUTRON STAR COUPLING TO ITS ENVIRONMENT

Marco Salvati
Institute of Space Astrophysics Frascati, Italy

Franco Pacini
Arcetri Astrophysical Observatory
University of Florence, Italy

ABSTRACT. We review facts, myths and theories related to the formation of neutron stars and their coupling to the environment.

1. Introduction

In this paper we will consider only rotation-powered neutron stars, of the kind which sooner or later in their lifetime become "normal" radio pulsars. Of course, neutron stars in accreting binary systems are also very strongly coupled to their environment, but they belong to a different class of astrophysical objects (accretion-powered sources).

We will discuss mainly the outward-bound flow generated by the rotating neutron star, rather than a complete two-way interaction. The discussion will include the identification of the various components of the flow (particles, waves, and time steady electromagnetic fields), the estimate of their densities, and the assessment of their contributions to the global energetics. The one-sidedness of our approach is justified because during most of the active lifetime the outflow occurs in the form of a highly supersonic wind, which cannot carry upstream the reaction of the environment. One important exception is the birth of the neutron star in supernova explosion, when the ejecta are contiguous to the collapsing core and the interaction proceeds effectively in both directions.

Following the introduction, the paper is divided in three sections, arranged in chronological order. Section 2 deals with the very beginning of a neutron star lifetime, and encompasses a few year interval from its birth. Here, as we said, the coupling is very strong and determines the initial conditions, which in turn determine the subsequent evolution of the star through the pulsar phase. The observational information relevant to Section 2 is scarce and indirect. One can try and deduce something about the initial conditions from the present-day distribution of pulsars in parameter space. One can also hope to learn something about newly born pulsars

D. J. Helfand and J.-H. Huang (eds.), The Origin and Evolution of Neutron Stars, 79–89.

from the radio emission which characterizes Population I Supernovae, provided that such emission is indeed attributable to pulsar activity.

In Section 3, we discuss young objects, aged between 10^3 and 10^4 years. Only a few such objects are known, but they are very active, and are the site of a number of different phenomena. Among these, most relevant to our understanding of the global output are the high frequency optical and X-ray pulsed emission from the star, and the time steady spatially extended emission from the plerion, i.e., the synchrotron nebula which the pulsar inflates within the surrounding medium.

Section 4 is devoted to aged neutron stars, from 10^5 years onward. This age bin contains most of the observed radio pulsars; the majority of them show up only through their radio pulsed emission. This radio emission is poorly understood and therefore it is not a good indicator of the large scale properties of the outflow. An exception is provided by the few cases where a small synchrotron nebula is observed; its origin and information content are analogous to the nebulae associated with the younger pulsars.

2. Pulsars At Birth

According to the commonly accepted scenario for neutron star formation, the evolution of the progenitor star is terminated by the collapse of the core and the explosive ejection of the envelope. In a conservative collapse the core angular velocity increases, and the magnetic field strength is amplified because of compression and differential rotation. It is thus expected that large magnetic stresses are built up between core and envelope, leading to a strong coupling. Although most Supernova models investigated until now do not incorporate the effects of rotation and magnetic fields in the collapse of the core and the expulsion of the outer layers, certainly those effects cannot be overlooked in real life.

Actually, from a purely energetic point of view, there is no difficulty in explaining through electromagnetic effects the expulsion of the outer layers and the entire SN phenomenon. This idea was put forward by Kardashev (1970), and elaborated upon by Ostriker and Gunn (1971), and Maceroni et al. (1974). Furthermore, in context of radio Supernovae, Bandiera et al. (1983) have pointed out that large stresses could induce the early fragmentation of the ejecta, and open low-opacity lines-of-sight to a central region.

The coupling between rotation and magnetic fields could also affect, in a major way, the final state of the collapsing core. We can give here two examples.

First, a simple minded expectation is that a strong magnetic field would result in a more effective removal of the core angular momentum, so that in a newly born neutron star field and rotation frequency could be anticorrelated. However, the anti-correlation between field and initial frequency can be argued against (Vivekanand and Narayan, 1981; Salvati, 1986) and may depend upon the ill-known details of the collapse.

Second, the speed of collapse could be substantially different depending on whether the magnetic field is able or not to rapidly remove the stellar angular momentum. If the field is strong and the angular momentum is removed quickly, rotation will not affect the stellar collapse which may take place very rapidly. The explosion of the outer layers would then be rapid and any binary system would be disrupted leading to the formation of fast moving pulsars. The fact that most pulsars are single stars has been interpreted as an evidence for the disruption of binary systems during the explosion of Supernovae. However, it has been pointed out that a relatively low magnetic field on the surface of the collapsing star would lead to much longer time-scales for the collapse and the explosion (Pacini 1983). Indeed the time-scale for removing angular momentum is proportional to B^{-2} and weakly magnetized neutron stars (10^8 - 10^{11} gauss, instead of the "standard" 10^{12} gauss) would be formed in a time ~ months (or even longer). This could be longer than the orbital period in a close binary system and the system would not be disrupted. Pulsars formed in this way would have low velocities. This scenario is consistent with the available evidence that all binary pulsars have weak fields and small scale heights, and with the observed correlation between fields and velocities (Anderson and Lyne, 1973). The same scenario provides a framework in which to discuss the origin of weakly magnetized, millisecond pulsars different from the generally accepted notion that these objects have been "rejuvenated" and spun up after an accretion phase (see, e.g. Van den Heuvel 1984). In particular, we note that in this framework one expects that millisecond pulsars should, in a large percentage of cases (reflecting the original situation), be in binary systems and lie close to the galactic plane (this fact is regarded as a puzzle in the generally accepted theory, see Bhattacharya and Srinivasan 1986).

The uncertainties in the theory could be reduced by more direct observations of newly born pulsars. In this respect, the radio Supernova phenomenon could prove of crucial importance. A comprehensive summary of all the available data, and a discussion of the main competing models can be found in Weiler et al. (1986). Here it will suffice to say that non-thermal radio emission appears to be associated with all SNe of type II and type I peculiar; the luminosity rises with time scales of days to months, first at high, then at low frequencies; when the opacity effects are negligible, the evolution is by and large approximated by a negative power of the elapsed time. Modeling the phenomenon as a newly born plerion (Pacini and Salvati, 1981) has the advantage of economy , since a single assumption is invoked for the radio SNe and the evolved Crab-like SN Remnants; within this scheme one naturally expects a continuity between the two classes of objects.

Indeed, the radio SN light curves can be extrapolated smoothly into Crab-type luminosities.

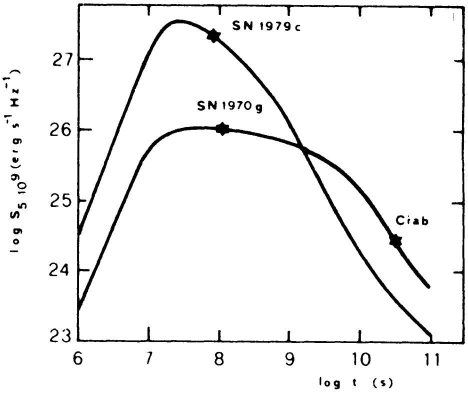

Fig. 1. Evolution of the radio flux at 5×10^9 Hz from two plerions. The upper curve postulates a central pulsar with $P_0 \sim$ ms inside a remnant expanding with $v \sim 10^9$ cm s^{-1}. The lower curve postulates a central pulsar with $P_0 \sim 16$ ms inside a remnant expanding with $v \sim 10^8$ cm s^{-1} (Crab-type parameters). Note how the Crab Nebula had initial properties very similar to those of the Supernova 1970 g.

In the mini plerion model the total non-thermal luminosity and its time decline are clues to the initial period and field of the central pulsar. The critical point remains the difficulty of detecting the newly born pulsar directly; the reliability of the model thus rests solely on the combined statistics of plerions and radio SNe, and especially on the (still very poor) statistics of intermediate age objects. These are predicted to fill-in the gap, or to be completely absent, according to the scenario which is adopted (Salvati, 1987).

3. Young, Energetic Pulsars

By the time an isolated neutron star reaches the age of Crab or Vela, its coupling to the surroundings has taken the comparatively simple form of a supersonic outflow. Also, the debris of the explosion have been swept away from the central zone, and the star is clearly visible as a pulsar. The radio pulses are not suited to the study of the global output: their luminosity is only a minute fraction of the total pulsed luminosity, not to mention the total rotational $\dot{E}$, and their interpretation is especially cumbersome since the radiation mechanism is coherent. The incoherent, high frequency pulses, instead, carry most of the power, and provide useful constraints on the emitting region.

3.1 Inferences from Observations

Several arguments suggest that the incoherent optical emission from fast pulsars is due to the synchrotron process, involving particles streaming away from the neutron star. The emitting region is thought to be in proximity of the "speed of light distance", or at least at a distance from the central star which is a constant fraction of this characteristic distance (Shklovsky, 1970; Pacini, 1971). The time averaged spectrum of the Crab pulsar turns over gradually from the UV to the optical and to the near IR (e.g., Middleditch et al., 1983). A reasonable interpretation is that the onset of synchrotron self-absorption is being observed. Then at the turn-over frequency the flux can be expressed in two independent ways as a function of the particle density per unit energy interval, the orthogonal component of the magnetic field, and the emitting volume. One has to make assumptions about the latter: for instance, the geometry appropriate to a fan beam would be an azimuthal slice, with thickness proportional to δP (δ is the pulse duty cycle) and height and depth proportional to P. It follows that the particle number flux, ϕ, and the typical Lorentz factor, γ, are

$$\phi \overset{\sim}{>} a \frac{L_\nu^3}{\nu^5 P^5 \delta^2}; \qquad \gamma \overset{\sim}{>} b \frac{L_\nu}{\nu^2 P \delta} \tag{1}$$

Here the constants a and b include universal constants, as well as our parameterization of the emitting volume; the inequality signs would apply if no turn-over were observed down the frequency ν. For the Crab pulsar one obtains the canonical numbers $\phi \simeq 10^{40}$ s^{-1}, $\gamma \simeq$ 1.3 10^2. Since Shklovsky's paper, though, two additional pulsars have been detected at optical frequencies, and the argument can, in principle, be extended to them. The Vela pulsar is very weak intrinsically, and no spectral information is available beside broad band colors (Manchester et al, 1978); eq. (1) reduces to a lower limit, so low as to be meaningless. The Magellanic Cloud pulsar PSR 0540-693 is quite similar to the Crab (Middleditch and Pennypacker, 1985); the lower critical frequency implied by the red color and the larger duty cycle tend to compensate in Eq. (1), so that Crab-like values for ϕ and γ do not appear unreasonable. Note that the power associated with the particle flux, mc^2 $\gamma\phi$, is less than the total available $\dot{E}$.

The outflow produced by a young, active pulsar inflates a bubble within the surrounding medium; the bubble emits synchrotron radiation, and exhibits a characteristic filled-center morphology. These so-called plerions are catalogued and discussed elsewhere, for instance in Weiler (1983). Four of them contain an observed pulsar, and represent the only known associations between pulsars and SNRs of any kind. They are the Crab Nebula, LMC 0540-693, MSH 15-52, and the Vela SNR (associated with PSR 0531+21 0540-693, 1509-58, and 0833-45, respectively).

The plerions work as integrators of the global pulsar output, the integration time being different for particles of different energies.

Detailed models have been built along these lines (Pacini and Salvati, 1973; Bandiera et al., 1984), and by parameter fitting one can discern the various components injected by the pulsars. For our purpose a simplified approach will be sufficient.

The spectrum of a typical plerion is flat in the radio domain, then it becomes steeper and steeper in the optical and in the X-rays. The bend is far from sharp, and does not correspond to the canonical change 0.5; nonetheless, we assume it to be due to synchrotron losses. We further assume that the age of the system is the slowing down time scale of the pulsar, and arrive at the following expressions

$$\gamma \simeq 1.6\ 10^5\ \nu_{13}^{2/3}\ t_{10.5}^{1/3}; \qquad \phi \simeq \frac{L}{mc^2\gamma}; \qquad B \simeq 7.1\ 10^{-7}\frac{\nu}{\gamma^2}\ \text{(Gauss)} \qquad (2)$$

When applied to the Crab nebula Eq. (2) gives $\gamma \sim 1.6\ 10^5$, $\phi \sim 7.8\ 10^{38}\ s^{-1}$, and $B \sim 2.3\ 10^{-4}$ G; for LMC 0540-693 the same quantities are $4.1\ 10^4$, $8.0\ 10^{38}\ s^{-1}$, and $4.2\ 10^{-4}$ G, respectively; in both cases there is approximate equipartition between particle and field energy. On the other hand the plerion component of MSH 15-52 is not detected, and the Vela plerion is so weak as to be reminiscent of the older nebulae described in Section 4 (Harnden et al., 1985). Notwithstanding all the uncertainties, the data indicate that the particle number flux at the nebula is roughly the same as at the pulsar. The associated power, instead, is much larger, and comparable with $\dot{E}$. We deduce that at the pulsar most of the energy flux must reside in carriers different from particles, either large amplitude waves or time steady e.m. fields.

We thus obtain a picture where the global outflow runs from the pulsar to the nebula with conserved total energy and total number flux. The individual particles are accelerated somewhere along the road, so that σ (the ratio of field energy to particle energy) starts $\gg 1$ and arrives ~ 1. For the sake of the following discussion, we stress that the latter condition is "observed" to hold only in the main body of the nebula: without a certain amount of modeling, nothing can be said about the behavior of σ in the intermediate zone.

3.2 Theories

We start from the pulsar side with a brief reminder of the basic electrodynamics (Gold, 1968; Pacini, 1968; Goldreich and Julian, 1969). The pulsar is modeled as a magnetized, rotating neutron star. Rotation and magnetization, plus a highly conductive constituent material, imply large potential differences, and most of the theory is about the ways of tapping this potential. The locus of the points where rigid corotation would take place at the speed of light is the light cylinder, and the field lines which do or do not cross the cylinder define the open and closed magnetosphere, respectively. Only the open magnetosphere is connected to the outside world, and the pulsar outflow originates from there; hence the relevant potential drop is the one occurring across the open magnetosphere, that is, in a dipole geometry,

$$\Delta V \sim 6.6\ 10^{12}\ \frac{B_{12}}{P^2}\ (\text{Volts})\,; \quad I \sim 5.9\ 10^{11}\frac{B_{12}}{P^2}(\text{Amps})\,; \quad \dot{E} \sim I\Delta V \qquad (3)$$

In Eq. (3) a characteristic current is also given; it corresponds to the sign reversal of the light cylinder field (again estimated in a dipole geometry) over a light cylinder radius. It has long been known that for the Crab pulsar $I/e \sim 1.310^{34}\ s^{-1}$, much less than the particle flux estimated from the optical pulses (the real currents must not be completely charge separated). At any rate, the power $I\ \Delta V$ is a good approximation to $\dot{E}$ in all variants of the model.

In an empty magnetosphere ΔV would appear both across and along the field lines; since along the lines there is negligible resistivity, a real magnetosphere becomes filled up with plasma, distributed so as to cancel out ΔV (parallel). The asymptotic condition ΔV (parallel) = 0 cannot be reached everywhere, and the regions where it is violated-the gaps-are suited to particle acceleration. With some subtle exceptions, ΔV (gap) is substantially smaller than ΔV (pulsar). Its growth is limited by electro-optical cascades, ignited by gap-energized primary particles. Then I (gap) and the energy production rate depend on how many field lines cross the accelerating region.

The various types of gaps, their location, their efficiency and relevance within the global machinery are the subject of a specialized literature (see, for instance, Ruderman and Sutherland, 1975; Ruderman, 1987; Arons and Scharlemann, 1979; Arons, 1983). A few important points can be extracted, on which a satisfactory consensus has been reached.

The gaps occurring close to the star surface produce very low powers; they might be relevant to the radio pulsed emission, and under this assumption one reproduces the death line as observed in the P-$\dot{P}$ diagram. The gaps occurring at higher altitudes are wider, and produce larger powers; this is still less than $\dot{E}$, but is sufficient to account for the high frequency pulsed radiation of young pulsars. Even if the overall energetics are settled, the details of the radiation mechanisms are not. The particle number flux is much larger than the minimum charge-separated flux estimated before. The multiplication is due to electro-optical cascades, so the main constituents are e^+ e^- pairs. Without straining the model parameters too much, it is possible to reproduce the "observed" fluxes; note however that an agreement on integral quantities-energy and number-does not necessarily imply an agreement on distribution shape.

As for the theory of plerions, we have seen that kinematical models allow one to quantify the various components to be injected. In order to connect the plerion to the pulsar wind one needs dynamical models, which take into account spatial gradients (Rees and Gunn, 1974; Kennel and Coroniti, 1984). The incoming wind is highly relativistic, and must be slowed down to the speed of the plerion boundary; this is achieved through a shock, which can be strong enough, i.e. effective enough in decelerating the flow, only if the upstream energetics are dominated by the particles, $\sigma \ll 1$. After the shock σ is also small, but the particle pressure does work on the field until in the main body of the nebula a rough equipartition is established.

We see that theory and observation are in order-of-magnitude agreement at the two ends of the flow; only, we do not know how to put the two pieces together. There is a region outside the light cylinder and inside the inner plerion boundary where, all other quantities conserved, σ changes from $\gg 1$ to $\ll 1$, and we have no information, theoretical or observational, on how this change comes about.

It might be that large amplitude waves plays a role in this context; they cannot propagate in a density much larger than the charge-separated one (Asseo et al., 1981), and their energy must be transferred to the particles. The details are unclear, and at any rate at the light cylinder one expects approximate equipartition between wave component and steady e.m. components: even if the radiation reaction were negligible, this would imply $\sigma \sim 1$, only half-way to what is needed.

3.3 Acceleration of Heavy Ions

If spin axis and magnetic axis point to the same hemisphere, so that electrons are required above the polar caps, the presence or absence of ions in the pulsar outflow depend on the ill-known structure of the return currents. However, one pulsar out of two should be born with antipodal axes, and should inject a ion flux equal to the charge-separated minimum. No multiplication occurs, since the ions cannot ignite electro-optical cascades; for this one needs stray electrons, which guarantee a pair plasma and a gap structure analogous to the previous case (Arons, 1983). The ions go through the same potential differences as the pairs, so the energy flux associated with them is likewise $\ll \dot{E}$.

A distinguishing feature of the ions is that they can attain the maximum energy corresponding to the given ΔV, whereas their lighter counterparts are limited by radiation reaction. Hence the 10^{15} eV radiation from the Crab pulsar could only arise from ions, and-if confirmed-would provide a strong indication that heavy particles are being accelerated.

4. X-ray Nebulae Around Aged Pulsars

The Einstein satellite has surveyed a sample of radio pulsars, old enough for the SN Remnant to be completely dissipated. The sample members were selected according to small distance and large $\dot{E}$, so as to maximize the probability of detection. At the position of three of them-namely, PSR 0355+54, 1055-52, and 1642-03-time steady, spatially extended emission was detected (Helfand, 1983). The author interprets his results as evidence of a threshold effect, whereby all and only the pulsars with $\dot{E} > 10^{34}$ erg s^{-1} maintain around them synchrotron nebulae roughly 1% efficient.

The nebulae differ by orders of magnitude in surface brightness, but even the most diffuse ones could hardly be confined by the static pressure of the interstellar medium. The source around PSR 1055-52 is definitely out of balance; a dynamic confinement is possible, if the pulsar is moving at a few 100 km s^{-1} in a density of a few cm^{-3} (Cheng, 1983). If we take an equipartition field of the order of 10^{-4}-10^{-5} gauss, the production of X-rays via the synchrotron process requires accelerating potentials of $\simeq 10^{14}$ volts. It is interesting to note that, according to Eq. (3), the maximum available ΔV falls in this range precisely when $\dot{E}$ is around 10^{34} erg s^{-1}.

In our view the agreement provides comforting evidence that the pulsar outflow continues into the middle age; that the global properties of the magnetosphere are described by eq. (3); and, finally, that the models based on the gap idea are right in predicting less and less pair production in older and older pulsars: in the end, the gaps widen to include the entire magnetosphere and the full ΔV (pulsar) becomes available locally.

5. Conclusions

The basic principles of a pulsar's working are, we think, rather firmly established. The structure of the magnetosphere, the pair production, the fate of the large amplitude waves, the asymptotic behavior of the wind are at least qualitatively understood.

There remain a few key points which have not yet been worked out, albeit grossly. One such point is the problem of the initial conditions in which a neutron star is born; here the most plausible approach is the improvement of the statistics and the assessment of the selection effects both in the P-$\dot{P}$ diagram and in the radio SN evolution.

The presence of heavy ions in the flow can be proven in a clearcut way by the detection of pulsed ultra high energy radiation, although in practice the issue is not so straightforward.

Finally, the problems about the flow properties in the intermediate region are well exemplified by the actual observations of the Crab nebula. There the region from the pulsar to the wisps (which are believed to mark the position of the shock and the beginning of the plerion) is completely black. The same blackness is a good representation of the state of our understanding of the detailed physical process produced by the pulsars but taking place in the extended volume which surrounds the central star.

Acknowledgements

One of us (F.P.) gratefully acknowledges the hospitality of the Center for Astrophysics, Cambridge Massachusetts and the partial support of NASA Contract 8-30751 while this paper was being written.

References

Anderson, B., and Lyne, A.G.: 1983, Nature 303, 597
Arons, J.: 1983, Astrophys. J. 266, 215
Arons, J., and Scharlemann, E.T.: 1979, Astrophys.J. 231, 854
Asseo, E., Llobet, X., and Pellat, R.: 1981, in "Pulsars", Proceedings of IAU Symp. No. 95, eds. W. Sieber and Wielebinski, Reidel, Dordrecht, p. 53
Bandiera, R., Pacini, F., and Salvati, M.: 1983, Astron. Astrophys. J. 126, 7
Bandiera, R., Pacini, F., and Salvati, M.: 1984, Astrophys. J. 285, 134
Bhattacharya, D., and Srinivasan, G.: 1986, Curr. Sci. 55, 327
Cheng, A.F.: 1983, Astrophys. J. 275, 790
Gold, T.: 1968, Nature 218, 731
Goldreich, P., and Julian, W.H.: 1969, Astrophys. J. 157, 869
Harnden, F.R., Grant, P.D., Seward, F.D., and Kahn, S.M.: 1985, Astrophys. J. 299, 828
Helfand, D.J.: 1983, in "Supernova Remnants and their X-ray Emission", Proceedings of IAU Symp. no. 101, eds. I.J. Danziger and P. Gorenstein, Reidel, Dordrecht, p. 471
Kardashev, N.S.: 1970, Soviet Astron. AJ 14, 375
Kennel, C.F., and Coroniti, F.V.: 1984, Astrophys J. 283, 694
Maceroni, C., Salvati, M., and Pacini, F.: 1974, Astrophys. Space Sci. 28, 205
Manchester, R.N., et al.: 1978, MNRAS 184, 159
Middleditch, J., and Pennypacker, C., and Burns M.S.: 1983, Astrophys. J. 273, 261
Ostriker, J., and Gunn, J.: 1971, Astrophys. J. 164, L95
Pacini, F.: 1968, Nature 219, 145
Pacini, F.: 1983, Astron. Astrophys. 126, L11
Pacini, F.,and Salvati, M.: 1973, Astrophys. J. 186, 249
Pacini, F., and Salvati, M.: 1981, Astrophys. J. 245, L107
Rees, M.J., and Gunn, J.E.: 1974, MNRAS 167, 1
Ruderman, M.A.: 1987, in "High Energy Phenomena around Collapsed Stars", Proceedings of a NATO ASI held in Cargese in September 1985, ed. F. Pacini.
Ruderman, M.A., and Sutherland, P.: 1975, Astrophys. J. 199, 51
Salvati, J.: 1987, in "High Energy Phenomena around Collapsed Stars", Proceedings of a NATO ASI held in Cargese in September 1985, ed. F. Pacini.
Shklovsky, I.S.: 1970, Astrophys. J. 159, L77

van den Huevel, E.P.J.: 1984, J. Astrophys. Astron. 5, 209

Vivekanand, M., and Narayan, R.: 1981, J. Astrophys. Astron. 2, 315

Weiler, K.W.: 1983, in "Supernova Remnants and their X-ray Emission", Proceedings of IAU Symp. no. 101, eds. I.J. Danziger and P. Gorenstein, Reiden, Dordrecht, p. 299

Weiler, K.W., Sramek, R.A., Panagia, N., van der Hulst, J.M., and Salvati, M.: 1986, Astrophys. J. 301, 790