Neutron Stars, Pulsars and Supernova Remnants: concluding remarks

F. Pacini\textsuperscript{1,2}
\textsuperscript{1} Arcetri Astrophysical Observatory, L.go E. Fermi, 5, I-50125 Firenze, Italy
\textsuperscript{2} Dept. of Astronomy and Space Science, University of Florence, L.go E. Fermi, 2, I-50125 Firenze, Italy

1. Introduction

More than 30 years have elapsed since the discovery of pulsars (Hewish \textit{et al.} 1968) and the realization that they are connected with rotating magnetized neutron stars (Gold 1968; Pacini 1967, 1968). It became soon clear that these objects are responsible for the production of the relativistic wind observed in some Supernova remnants such as the Crab Nebula.

For many years, the study of pulsars has been carried out mostly in the radio band. However, many recent results have come from observations at much higher frequencies (optical, X-rays, gamma rays). These observations have been decisive in order to establish a realistic demography and have brought a better understanding of the relationship between neutron stars and SN remnants.

The Proceedings of this Conference cover many aspects of this relationship (see also previous Conference Proceedings such as Bandiera \textit{et al.} 1998, Slane and Gaensler, 2002). Because of this reason, my summary will not review all the very interesting results which have been presented here and I shall address briefly just a few issues. The choice of these issues is largely personal: other colleagues may have made a different selection.

2. Demography of Neutron Stars: the role of the magnetic field

For a long time it has been believed that only Crab-like remnants (plerions) contain a neutron star and that the typical field strength of neutron stars is $10^{12}$ Gauss. The basis of this belief was the lack of pulsars associated with shell-type remnants or other manifestations of a relativistic wind. The justification given is that some SN explosions may blow apart the entire star. Alternatively, the central object may become a black hole. However, the number of shell remnants greatly exceeds that of plerions; it becomes then difficult to invoke the formation of black holes, an event much more rare than the formation of neutron stars.

The suggestion that shell remnants such as Cas A could be associated with neutron stars which have rapidly lost their initial rotational energy because of an ultra-strong magnetic field $B \sim 10^{14} - 10^{15}$ Gauss (Cavaliere \& Pacini, 1970) did receive little attention. The observational situation has now changed: a compact thermal X-ray source has been discovered close to the center of Cas A (Tananbaum, 1999) and it could be the predicted object. Similar sources have been found in association with other remnants and are likely to be neutron stars. We have also heard during this Conference that some shell-type remnants (including Cas A) show evidence for a weak non-thermal X-ray emission superimposed on the thermal one: this may indicate the presence of a residual relativistic wind produced in the center. Another important result has been the discovery of neutron stars with ultra-strong magnetic fields, up to $10^{14} - 10^{15}$ G. In this case the total magnetic energy could be larger than the rotational energy ("magnetars"). This possibility had been suggested long time ago (Woltjer, 1968). It should be noticed, however, that the slowing down rate determines the strength of the field at the speed of light cylinder and that the usually quoted surface fields assume a dipolar geometry corresponding to a braking index $n = 3$. Unfortunately the value of $n$ has been measured only in a few cases and it ranges between 1.4 $-$ 2.8 (Lyne \textit{et al.}, 1996).

The present evidence indicates that neutron stars manifest themselves in different ways:

- Classical radio pulsars (with or without emission at higher frequencies) where the rotation is the energy source.
- Compact X-ray sources where the energy is supplied by accretion (products of the evolution in binary systems).
- Compact X-ray sources due to the residual thermal emission from a hot surface.
- Anomalous X-ray pulsars (AXP) with long periods and ultra strong fields (up to $10^{15}$ Gauss). The power emitted by AXPs exceeds the energy loss inferred from the slowing down rate. It is possible that AXPs are associated with magnetized white dwarfs, rotating close to the shortest possible period (5 $-$ 10 s) or, alternatively, they could be neutron stars whose magnetic energy is dissipated by flares.
- Soft gamma-ray repeaters.
In addition it is possible that some of the unidentified gamma ray sources are related to neutron stars. The present picture solves some previous inconsistencies. For instance, the estimate for the rate of core-collapse Supernovae (roughly one every 30-50 years) was about a factor of two larger than the birth-rate of radio pulsars, suggesting already that a large fraction of neutron stars does not appear as radio pulsars.

The observational evidence supports the notion of a large spread in the magnetic strength of neutron stars and the hypothesis that this spread is an important factor in determining the morphology of Supernova remnants. A very strong field would lead to the release of the bulk of the rotational energy during a short initial period (say, days up to a few years); at later times the remnant would appear as a shell-type. A more moderate field (say $10^{12}$ Gauss or so) would entail a long lasting energy loss and produce a plerion.

3. Where are the pulses emitted?

Despite the great wealth of data available, there is no general consensus about the radiation mechanism for pulsars. The location of the region where the pulses are emitted is also controversial: it could be located close to the stellar surface or, alternatively, in the proximity of the speed of light cylinder.

The radio emission is certainly due to a coherent process because of the very high brightness temperatures ($T_b$ up to and above $10^{30}$ K have been observed). A possible model invokes the motion of bunches of charges sliding along the curved field lines with a relativistic Lorentz factor $\gamma$ such that the critical frequency $\nu_c \sim \frac{\gamma^3}{c}$ reaches or exceeds the radio band. Typically, this would entail $\gamma \gtrsim 10^2$.

If we assume $T_b \sim 10^{30}$ K and $\gamma \sim 10^2 - 10^3$, the thermodynamical limitation $kT_b \sim mc^2\gamma F$ requires a coherence factor $F$ (number of electrons in the bunch) of order $\sim 10^{17}$. At least one of the sizes of the bunch must be smaller than the emitted wavelength. The radio spectrum is determined by the distribution in size of the bunches and the effect of coherence is gradually lost at very high radio frequencies (Aloisio & Blasi 2002). This may possibly explain the up-turn of the spectrum observed in some sources in the millimeter range, as reported here by Sieber.

Unfortunately the radio emission does not give sufficient information about the parameters of the source since many of them are affected by the degree of coherence. The situation is different if we consider pulsars which emit at higher frequencies (optical and X-ray bands), where the observed brightness is compatible with an incoherent process.

A striking aspect of the optical pulses is the very strong dependency of the power upon the period (they are emitted only from a few sources).

A possible scenario assumes that the optical radiation is normal synchrotron radiation, emitted from particles which gyrate with a small pitch angle $\Psi$ around the field lines. Such a model, applied to the Crab pulsar, PSR 0531, can explain the observations with parameters compatible with those expected at the speed of light cylinder distance $R_L = \frac{\gamma c}{B^2}; \Psi \sim 10^{-2}; B_\perp \sim 10^4$ G; $\gamma \sim 10^2 - 10^4$.

The model leads to the expectation of a very fast decrease of the synchrotron intensity with period because of the combination of two factors: a) the reduced particles flux when the period increases; b) the reduced efficiency of synchrotron losses (which scale $\propto B^2 \times R_L^{-6} \propto P^{-6}$) at the speed of light cylinder (Pacini, 1977; Pacini & Salvati 1983, 1987). The prediction fits the observed secular decrease of the optical emission from the Crab Nebula and the magnitude of the Vela pulsar. A recent re-examination of all available optical data confirms that this model can account for the luminosity of the known optical pulsars (Shearer and Golden, 2001).

If so, the optical radiation supports strongly the notion that the emitting region is located close to the speed of light cylinder.

4. A speculation: can the thermal radiation from young neutron stars quench the relativistic wind?

My final remarks concern the possible effect of the thermal radiation coming from the neutron star surface upon the acceleration of particles. This problem has been investigated for the near magnetosphere (Supper & Truemper, 2000) and it has been found that the Inverse Compton Scattering (ICS) against the thermal photons is important only in marginal cases. However, if we assume that the acceleration of the relativistic wind and the radiation of pulses occur close to the speed of light cylinder, the situation becomes different and the ICS can dominate over synchrotron losses for a variety of parameters.

The basic reason is that the importance of ICS at the speed of light distance $R_L$ scales like the energy density of the thermal photons $u_{\gamma} \propto R_L^{-2} \propto P^{-2}$; on the other hand, the synchrotron losses are proportional to the magnetic energy density in the same region $u_B \propto R_L^{-6} \propto P^{-6}$.

Numerically, one finds that ICS losses dominate over synchrotron losses if

$$T_b > 0.4 \frac{B_1^{1/2}}{P_s}$$

where $T_b$ is the temperature in units $10^6$ K; $B_{12} = \frac{B}{10^{12} \text{G}}$; $P_s$ is the pulsar period in seconds).

The corresponding upper limit for the energy of the electrons, assuming that the acceleration takes place for a length of order of the speed of light distance and that the gains are equal to the losses is given by:

$$E_{\text{max}} \simeq 1.2 \times 10^3 T_b^{-4} P_s \text{ GeV}.$$
Provided that the particles are accelerated and radiate in proximity of the speed of light cylinder distance, we conclude that the thermal photons can limit the acceleration of particles, especially in the case of young and hot neutron stars. It becomes tempting to speculate that this may postpone the beginning of the pulsar activity until the temperature of the star is sufficiently low. The main manifestation of neutron stars in this phase would be a flux of high energy photons in the gamma-ray band, due to the interaction of the quenched wind with the thermal photons from the stellar surface. This model and its observational consequences are currently under investigation (Amato, Blasi, Pacini, work in progress).

References
Aloisio, R., & Blasi, P. 2002, Astrop. Phys.,
Bandiera, R., et al. 1998, Proc. Workshop "The Relationship between Neutron Stars and Supernova Remnants", Mem. Societ Astronomica Italiana, vol. 69, n. 4
Cavaliere, A., & Pacini, F. 1970, ApJ, 159, 170
Gold, T. 1968, Nature, 217, 731
Hewish A., et al. 1968, Nature 217, 709
Lyne, G., et al. 1996, Nature, 381, 497
Pacini, F. 1967, Nature, 216, 567
Pacini, F. 1968, Nature, 219, 145
Pacini, F. 1971, ApJ, 163, L17
Pacini, F., & Salvati, M. 1983, ApJ, 274, 369
Pacini F., & Salvati, M. 1987, ApJ., 321, 447
Shearer, A., and Golden, A. 2001, ApJ, 547, 967
Slane, P., Gaensler, B. 2002, Proc. Workshop "Neutron Stars in Supernova Remnants" ASP Conference Proceedings (in press)
Supper, R., & Trumper, J. 2000, A&A, 357, 301
Tananbaum, B., et al. 1999, IAU Circular 7246
Thompson, C., Duncan, R.C. 1996, ApJ, 473, 322
Woltjer, L. 1968, ApJ, 152, 179