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New perspectives in pulsar research

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Abstract. The new discoveries of the Parkes pulsar search experiments, are triggering a stimulating intellectual context among the observational and theoretical groups working in pulsar related fields in our country. We have set up a collaboration program funded by Minister of Research (MIUR) in order to create a training opportunity for PhD students and young fellows. In this paper we report the main results achieved so far.

Key words. Galaxy: globular clusters: individual: NGC 6397, NGC 6752 – stars: pulsars: individual: PSR J1740–5340 – stars: binaries: close – stars: binaries: evolution – stars: supernovae: general

1. Introduction

Pulsars, rapidly rotating highly magnetized neutron stars, have many exciting applications in physics and astronomy. A neutron star is produced when nuclear reactions in the core of a massive star can no longer release the energy required to sustain it against gravitational collapse. In one of the most spectacular events in nature, the inner core collapses in a fraction of a second, while the outer layers are suddenly and explosively expelled in a supernova. What remains is an object slightly more massive than the Sun, but with a radius of only 10 km: in effect, a huge atomic nucleus. Because a neutron star spins and is highly magnetized, it radiates collimated beams of radio waves which we observe as pulses, light-house-like, once per rotation. After 30 years since the original discovery, pulsar research has great vitality, making major contributions to field ranging from ultra-dense matter physics to relativistic

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gravity, cosmology and stellar evolution. A striking example has been the confirmation of the existence of gravitational radiation, as predicted by Einstein's general theory of relativity. Using new generation equipments and the 64-m radiotelescope near Parkes (NSW, Australia) we are now producing a significant boom of radio pulsar counting. A new survey of the Galactic disk, the Multibeam Pulsar Survey, still in progress (D'Amico et al. 2000; Manchester et al. 2001), has already discovered more than 600 new radio pulsars (to be compared to the about 700 radio pulsars discovered in about 30 years since the original one). These discoveries are triggering a stimulating intellectual context, which has revealed to be the ideal ground to consolidate a collaboration network existing among the observational a theoretical groups working in pulsar related fields in our country, and to create a training opportunity for PhD students and Post-Docs.

One interesting subject of pulsar research is the understanding of young (age less than 100,000 years) pulsars. These objects are relatively rare in the population, and even more rare in the observed sample. They are intrinsically rare because they evolve relatively fast. Then, the density of young pulsars in the Galaxy is relatively low, and their distance is, on average, relatively high. Also, young pulsars tend to be found at low Galactic latitudes, close to their birth place. The observation of distant pulsars at low Galactic latitudes is limited by the dispersion and scattering of pulses in the interstellar medium, so young pulsars are even more rare in the observed sample. On the other hand, young pulsars are very interesting objects. For instance, they are often associated with the supernova remnant (SNR). Traditionally, the material expelled during the supernova explosion produces the typical shell structure of many SNRs. A pulsar at the centre of a SNR, being a source of strong magnetic field and relativistic particle beams, might interact with the SNR leading to the observation of plerionic structures. The study of pulsar/SNR associations provides useful information on pulsar winds, on the physical process taking place in plerions, and on the interaction between plerionic and filamentary components. Young pulsars show often period irregularities and glitches which are very useful in the understanding of the interior structure of neutron stars (Wang et al. 2000). Young pulsars are also often detectable at high energies (X and gamma). It is believed that a substantial fraction of the unidentified Galactic gamma ray sources can be young pulsars (Gehrels et al. 2000).

Other systems relatively rare in the population but very interesting, are the binary systems containing a pulsar with a neutron star companion. In this case, the 'clock' signal of the pulsar can be used to probe relativistic effects in the strong gravitational field of the companion (Kaspi et al. 2000).

Other rare interesting systems are binary systems containing a pulsar with a non compact companion. For instance, in the system containing the pulsar PSR B1259-63 and a Be-type companion, the pulsar signal has been used in the study of the stellar disk associated with the Be star (Johnston et al. 1996).

Using new generation pulsar search experiments and the 64-m radiotelescope near Parkes (NSW, Australia), the Italian Group in collaboration with research groups at ANTF (Australia), Jodrell Bank (UK), MIT (USA) and Columbia University (USA), is producing a boom of pulsar discoveries. The survey of the Galactic plane (the Parkes Multibeam Pulsar Survey), still in progress (D'Amico et al. 2000; Manchester et al. 2001), has discovered so far more than 600 new radio pulsars (to be compared to the about 700 pulsars discovered in 30 years, since the original discovery). The most interesting aspect of the experiment is in fact the discovery of several objects intrinsically rare, like young pulsar (D'Amico et al. 2001c), dual neutron star systems (Lyne et al. 2000), and binary pulsars with massive companions (Stairs et al. 2001).

These results, and those which will be available when the new observations and the data processing will be fully completed, will represent a new unprecedented observational panorama to study the young pulsars, the associations pulsar/SNR, and to address all the interesting issues mentioned above.

Another interesting aspect of pulsar research is the understanding of millisecond pulsars. These are pulsars with spin periods of the order of few millisecond and very low magnetic fields (typically 3-4 decades smaller than 'normal' pulsars). It is believed that millisecond pulsars are formed when a neutron star in a binary system with a low mass companion is spun-up as a result of mass accretion from the evolving companion. Clock stability in millisecond pulsars is observed to be very high, comparable to the best time-standard available on earth, so they are useful for high precision timing. Even more interesting are the millisecond pulsars found in Globular Clusters, because they provide constraints on the dynamical status of the host cluster, on the neutron star content of the cluster, and on the role of binaries in the dynamical evolution of clusters. Using the same equipment at Parkes, we are performing a deep search of the Globular Cluster System for new millisecond pulsars. Preliminary results (D'Amico et al. 2001a,b) indicate that also this experiment is a very promising one, having discovered so far 12 new millisecond pulsars in 6 clusters which were not known to possess pulsars, bringing the number of clusters containing millisecond pulsars to 18. Among these discoveries there are peculiar objects, like for instance a millisecond pulsar in a tiny binary system with a companion of planetary mass (D'Amico et al. 2001a).

Several factors contribute to make the Parkes experiments as successful as they are. First, the recent upgrade of the telescope, consisting in the availability of 'multibeam' receiver operating at 1.4 GHz, having wide band feeds and very low system noise temperature (about 20 K). Observations at 1.4 GHz (with respect to the traditional observations at the lower frequency of 400 MHz) are less affected by dispersion and scattering in the interstellar medium. The wide band (288 MHz at 1.4 GHz) and low receiver temperature result in a very high instantaneous sensitivity. We have also participated to the installation of a new sensitive back end, which further improved the system capabilities. The availability of new generation data storage devices, like the DLT tapes (with a capacity of 35 Gbytes per tape), allows to perform long integrations (35 minutes for the Galactic plane survey, and up to 2.3 hours per target for the globular clusters search), resulting in unprecedented sensitivity levels. Beside observing, one of the major tasks of these new generation pulsar search experiments is the data handling and data processing. The Parkes experiments involve several hundreds DLT tapes (so several thousands Gbytes) which requires the availability of supercomputing resources. The results achieved so far have been obtained using a network of several workstations available at Bologna, ATNF, Jodrell Bank and MIT. The next logical step of the pulsar experiments is a new search at high Galactic latitudes. This survey will be complementary to the survey of the Galactic plane, and is expected to discover several millisecond pulsars in the Galactic field, many 'recycled' binary pulsars and additional relativistic binary pulsars. Substantially, this experiment will address a number of interesting issues, like the pulsar velocity distribution, the spin down dynamics, the magnetic field decay mechanism, and the formation and evolution of millisecond pulsars in the Galactic field. For the data processing of this experiment, and to complete a full acceleration analysis of the ongoing Galactic plane survey, a new dedicated powerful multiprocessor system has to be implemented on each institution of the Parkes collaboration.

In the following sections we report some interesting highlights of our research.

2. The peculiar millisecond pulsar binary in NGC 6397

The eclipsing MSP PSR J1740–5340, discovered by D'Amico et al. (2001a) in the globular cluster NGC 6397, has the longest orbital period ($P_{\rm orb} \simeq 32.5$ hr) and the most massive minimum companion mass (0.18 $M_\odot$) among the 10 eclipsing pulsars detected up to now. The spin period ($P_{\rm spin} \simeq 3.65 \times 10^{-3}$ s) and its derivative ($\dot{P} = 1.59 \times 10^{-19}$), recently derived by D'Amico et al. (2001b), allow the determination of the NS magnetic moment, $\mu_{26} \simeq 7.7$. Its position with respect to the cluster center excludes the possibility of a contamination of $\dot{P}$ due to the NS acceleration in the gravitational field of the cluster (D'Amico et al. 2001b), implying that the estimate of the NS magnetic moment is reliable. The optical counterpart of PSR J1740–5340, identified by Ferraro et al. (2001) with a slightly evolved turnoff star in the sample studied by Taylor et al. (2001) using data from the HST archive, also shows light modulation at the same orbital period as the radio data (Ferraro et al. 2001).

PSR J1740–5340 shows radio eclipses lasting for about 40% of the orbital phase at 1.4 GHz (D'Amico et al. 2001b). Out of eclipse the pulsar signal at 1.4 GHz shows significant excess propagation delays (up to $\sim$ 3 ms) and strong intensity variations. This suggest that in PSR J1740–5340 the signal is propagating through a dense material surrounding the system. In order to investigate this possibility, D'Amico et al. (2001b) have fitted the excess delays measured in two adjacent bands of 128 MHz each at 1.4 GHz. They found that the excess delays Δt can be well fitted with the equation $\Delta t \propto \nu^{-2.02\pm0.30}$ that strongly supports the hypothesis that the responsible mechanism is dispersion in a ionized medium. In this case the corresponding electron column density variations are $\Delta n_{\rm e} \sim 8 \times 10^{17} \Delta t_{-3}$ cm^{-2}, where Δt_{-3} is the delay at 1.4 GHz in ms. For $\Delta t_{-3} \sim 3$ the estimated electron column density is $\sim 2.4 \times 10^{18}$ cm^{-2}.

The eclipsing radius of the system is $R_{\rm E} \sim 4.4 \times 10^{11}$ cm (D'Amico et al. 2001b), taking $m_1 = 1.8$ $M_\odot$ for the NS mass and $m_2 = 0.45$ $M_\odot$ for the secondary mass (see below) and $P_{\rm orb} \sim 32.5$ hr. This radius is larger than the Roche lobe radius of the secondary ($\sim 1.3 \times 10^{11}$ cm). This means that the eclipsing matter is beyond the gravitational influence of the companion star and must be continuously replenished. From a simple calculation (see Burderi et al. 2002 for details), we can estimate a rough order of magnitude of the necessary mass loss rate from the secondary, $\dot{M}$, by assuming spherical symmetry (which is, however, not consistent with the randomly variable signal intensity shown by the radio data). We find $\dot{M}$ up to $\sim 0.6 \times 10^{-10}$ $M_\odot$ yr^{-1}. Even considering the uncertainty on this estimate, winds induced by the pulsar radiation are typically 2–3 orders of magnitude weaker (Tavani & Brookshaw, 1991). It is also unlikely that this matter is provided by the wind from the main sequence companion star, given that the mass loss rate due to the star wind is expected to be less than $\sim 10^{-12}$ $M_\odot$ yr^{-1}. We conclude that the mass loss rates we derive are more consistent with Roche lobe overflow driven by nuclear evolution of the secondary and orbital angular momentum mass loss, than with a possible wind from the secondary.

PSR J1740–5340 is likely to represent a system whose evolution has been envisioned by Burderi et al. (2001). If the mass transfer rate drops below the level required to allow the expansion of the magnetosphere beyond $R_{\rm LC}$, the emission from the rotating magnetic dipole will switch on (e.g. Illarionov & Sunyaev 1975; Stella et al. 1994). The pressure exerted by the radiation field of the radio pulsar may overcome the pressure of the accretion disk, thus determining the ejection of matter from the system. Once the disk has been swept away, the radiation pressure stops the infalling matter as it overflows the inner Lagrangian point. During this 'radio ejection' phase,

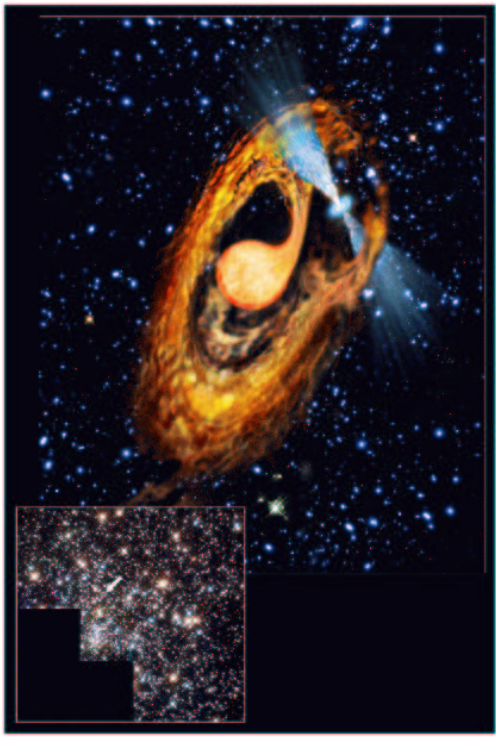

Fig. 1. An artistic impression of the system PSR J1740–5340 based on the scenario proposed in this paper (courtesy of ESO).

the mechanism that drives *mass overflow* from L_1 can well be active, but *the pulsar radiation pressure at* L_1 *prevents mass accretion onto the NS* (see Burderi et al. 2001).

The spin and the magnetic moment of the pulsar may keep the system in a radio-ejection phase in which accretion is inhibited by the radiation pressure exerted by the pulsar on the overflowing matter while the mechanism that drives the Roche lobe overflow from the companion is still active, thus causing an intense wind which would be very difficult to explain otherwise. This evolution seems to be the only viable possibility to explain the long lasting eclipses and the strong intensity variation randomly occurring in the radio emission. An artistic impression of the system, according to this scenario, is shown in Fig. 1.

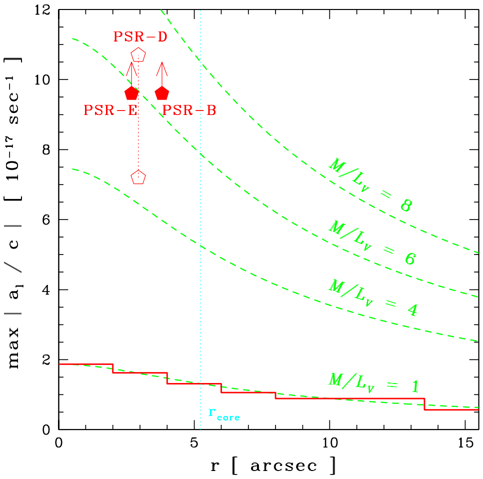

Fig. 2. Maximum line-of-sight acceleration $|a_1/c| = |\dot{P}/P|$ versus radial offset with respect to the center of NGC 6752. The histogram represents the prediction based on the star density profile of Ferraro et al. (2003) assuming a unity mass-to-light ratio. The dashed lines are analytical fits to the optical observations, labeled according to the adopted mass-to-light ratio. The measured values of $\dot{P}/P$ (filled pentagons, D'Amico et al. 2002) in the two MSPs with negative $\dot{P}$ (PSR−B and E) can be reproduced only for $\mathcal{M}/\mathcal{L}_V > 6-7$. The open pentagons show our best guessed range of maximum $|a_1/c|$ for PSR−D: the upper value is calculated assuming a negligible intrinsic positive slow down $\dot{P}_{sd}$; the lower value is estimated taking into account intrinsic $\dot{P}_{sd}$ from the observed scalings between X-ray luminosity and spin-down power for MSPs (see D'Amico et al. 2002 and reference therein).

3. The central mass to light ratio in NGC 6752

NGC 6752 is a core-collapsed cluster (Ferraro et al. 2003) with a very precise distance measurement: 4.1 kpc± 5%, obtained fitting the white dwarf (WD) sequence (Renzini et al. 1996). In this cluster a 3.26 ms binary pulsar was first discovered, and originally labeled PSR J1910−59A (D'Amico et al. 2001a). Amplification due to scintillation helped in the detection of four additional MSPs in the same cluster (hereafter PSRs B, C, D, E). All of them are isolated with spin periods in the range 4.6 − 9.0 ms. X-ray counterparts for PSR−D, PSR−C and PSR−B have been detected (Pooley et al. 2002; D'Amico et al. 2002) using a ~ 30 ksec exposure taken with the Chandra X-ray observatory.

PSRs B, D and E are located close to the cluster center, as expected as a consequence of mass segregation in the cluster. PSR−D has the third largest period derivative, $\dot{P} = 9.6 \times 10^{-19}$, among known MSPs and the large negative $\dot{P}$ values observed for PSR−B and E, allow to directly derive a lower limits to the line-of-sight accelerations ($a_l/c = \dot{P}/P = -9.6 \pm 0.1 \times 10^{-17}$ s^{-1}) that is the largest known after those of PSRs B2127+11A and D in the core of M15 (Anderson et al. 1990). Which is the origin of such acceleration? Given the location of NGC 6752 in the galactic halo and knowing its proper motion (Dinescu et al. 1999), it is possible to calculate the contributions to $\dot{P}$ due to centrifugal acceleration, differential galactic rotation and vertical acceleration in the Galactic potential, all of them resulting negligible (D'Amico et al. 2002). Given the very low probability (Ferraro et al. 2003) of the existence of a close perturber exerting a gravitational pull onto the pulsars, one can safely adopt the hypothesis (already applied to many globulars) that the line-of-sight acceleration of the MSPs with negative $\dot{P}$ is dominated by the overall effect of the cluster gravitational potential.

In this case, a lower limit to the projected mass-to-light ratio $\mathcal{M}/\mathcal{L_V}$ in the inner regions of NGC 6752 can be derived from the following rule, which holds to within ~10% in all plausible cluster models (Phinney 1992):

$$\left|\frac{\dot{P}}{P}(\theta_\perp)\right| < \left|\frac{a_{l,max}(\theta_\perp)}{c}\right| \simeq$$

$$\simeq 1.1\frac{G}{c}\frac{M_{cyl}(<\theta_\perp)}{\pi D^2\theta_\perp^2} =$$

$$= 5.1 \times 10^{-18}\frac{\mathcal{M}}{\mathcal{L}_V}\left(\frac{\Sigma_V(<\theta_\perp)}{10^4\ \mathrm{L_{V\odot}pc^{-2}}}\right)\mathrm{s}^{-1}.$$

Here $\Sigma_V(<\theta_\perp)$ is the mean surface brightness within a line of sight subtended by an angle $\theta_\perp$ with respect to the cluster center, $M_{cyl}(<\theta_\perp)$ is the mass enclosed in the cylindrical volume of radius $R_\perp = D\theta_\perp$ and $\mathcal{M}/\mathcal{L_V}$ is the mean *projected* mass-to-light ratio in the V band. In Fig. 2 the curves of maximum $|a_l/c|$ for different values of $\mathcal{M}/\mathcal{L_V}$ have been plotted, using the most recent published brightness profile for this cluster (Ferraro et al. 2003). In particular, in Fig. 2 the histogram represents the data for $\mathcal{M}/\mathcal{L_V}$=1. This greatly underestimates the observed values of $\dot{P}/P$. The dashed lines are good analytical fits to the observed data, scaled according to increasing values of $\mathcal{M}/\mathcal{L_V}$. Only $\mathcal{M}/\mathcal{L_V}$ >6-7 can account for the observed $|\dot{P}/P|$ of PSRs B and E.

This result provides the first direct dynamical evidence for a high density of unseen remnants in the core of a globular cluster. Typical mass-to-light ratios for the central regions of the globular cluster span the interval $\mathcal{M}/\mathcal{L_V}$=2−3.5 (Pryor & Meylan 1993), while using the same method applied to NGC 6752, a value ~ 3 was obtained by Phinney (1993) in the case of M15, a core-collapsed GC long suspected to host a central black-hole (see e.g. van der Marel & Roeland 1999). Taken at face, $\mathcal{M}/\mathcal{L}_V > 6-7$ would imply the existence of > 1500 M$_\odot$ of low-luminosity matter within the inner 0.08 pc of NGC 6752 (equivalent to the projected displacement of PSR−B from the cluster barycenter). In principle, it could be constituted either by a massive black hole (like the $\approx 1700^{+2700}_{-1700} M_\odot$ black hole in the center of the globular cluster M15 recently reported by Gerssen et al. 2002) or by a high central concentration of dark remnants of stellar evolution, like neutron stars and heavy white dwarfs (as also proposed for M15 by Gerssen et al. 2002 and Baumgardt et al. 2002). Finding evidences

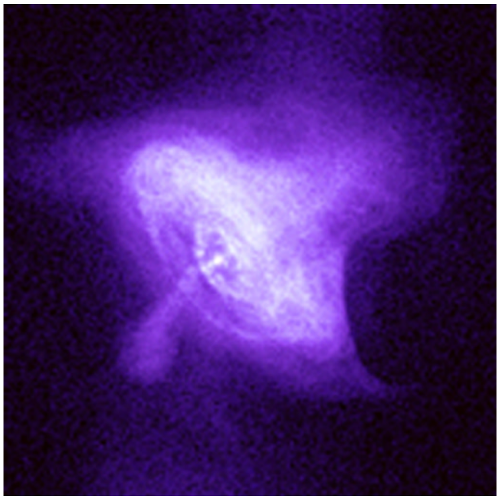

Fig. 3. Chandra X-rays image of the torus-jet pattern in the Crab Nebula.

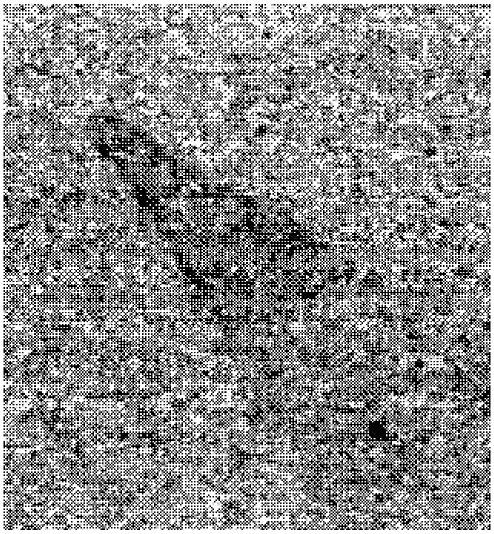

Fig. 4. Hubble Hα image of the head of Guitar Nebula.

for the presence of stellar (or more massive) black-holes in globular clusters is a difficult task. These results show that NGC 6752 could be a primary target for such a search.

4. Supernova remnants and pulsar wind nebulae

Supernova remnants (SNRs) are nebulae originated from a stellar explosion, known as a supernova event. Core-collapse supernovae leave behind also a degenerate stellar remnant. In the case of a fast spinning magnetized neutron star, its rotational energy is released by magnetic dipole radiation and thus provides a late energy input to the nebular remnant (like in the Crab Nebula, Fig. 3), mostly in the form of magnetic fields and relativistic particles. A magnetic bubble (called 'plerion') is then created, in which relativistic electrons emit synchrotron radiation from radio wavelengths up to X rays. Its global properties can be modelled in terms of the injected quantities as well as of evolutive effects (Reynolds & Chevalier 1984; Bandiera et al. 1984).

A fundamental issue is by what physical mechanisms the pulsar may accelerate particles with the required energy spectrum to match observations. A widely accepted model (Kennel & Coroniti 1984a,b) requires that a highly relativistic magnetohydrodynamic (MHD) pulsar wind is effectively slowed down by the outer medium, and that particle acceleration occurs at the wind termination shock (in the Crab Nebula at the location of the so-called 'wisps'). This implies that the pulsar wind must have a ratio between Poynting flux and kinetic-energy flux (called 'sigma') as small as 0.01-0.001. But this wind is magnetically, driven, and then at the base sigma must be > 1: this problem is called the 'sigma paradox'. Many models (e.g. Michel 1994; Lyubarsky & Kirk 2001) introduce a transition from a high to a low sigma but none of them is fully satisfactory. As we shall see below, also the particle acceleration at the termination shock is not fully understood yet. Actual models seems to require the presence of a non negligible fraction of protons in the pulsar wind. Protons interact at the wisps location with magnetic field and electron positron pair plasma via resonant cyclotron processes so to transfer energy from the magnetic field to the leptonic component, and accelerate electrons to power law distribution. This model allows also to explain the time variation of the wisps structure as a wave like pattern. We are involved in particle simulations of electron acceleration at shock and energy transfer. Till now no evidence of protons in the pulsar wind nebula have been found mainly because their syncrotron radiation is much less than that of electrons; however it will be possible in the next future to detect neutrino flux from p-p scattering or at least to set an upper limit on the proton density. There is also an evidence of an excess at mm wavelengths (Bandiera et al. 2002) which implies a different origin for the radio emitting electrons from those emitting in the infrared and beyond (the latter component being in agreement with what predicted by Kennel & Coroniti 1984a,b).

Recent observations show that the wisps are highly dynamical, both in the Crab Nebula and in Vela SNR. A key problem is to what extent the properties of the associated pulsar are related to those of the nebula. From the classical evolutive equations it can be shown that highly magnetized pulsars do not generate long lived plerions, because they release their spin energy in a short time. In general, candidate high-B neutron stars like Anomalous X-ray Pulsars, Soft Gamma Repeaters, or non pulsating X-ray Point-like Sources are associated with SNRs without any evident plerionic component. But it has also been shown that, while pulsar J1119−6127 (high-B pulsar) is associated with the shell-like SNR G292.2−0.5 (Pivovaroff et al. 2001), pulsar J1846−0258 (with similar age and surface field) drives in Kes 75 a bright plerionic component. This may be the result of different wind efficiencies (Mereghetti et al. 2002). In a simple-minded approach the field injected by a spinning star is expected to be toroidal, while the particles should move with the field. But, in this case, in the Crab Nebula the radial flow would turns out to be too slow to account for the X-ray nebular extension observed (see e.g. Amato et al. 2000). Ways to overcome this problem imply either a different field geometry, or a high efficiency of diffusive processes, or else additional acceleration sites beyond the wisps.

There are also pulsar wind nebulae with a distinct bow shock-like structure (Fig. 4), shaped by the pulsar motion with respect to the ambient medium: either the outer SNR, like W44, IC 443 (Bocchino & Bykov 2001) or N157B, or the interstellar medium, like for the nebulae of PSR B2224+65 (the Guitar Nebula; see Chatterjee & Cordes 2002), B1957+20, J0437−4715 and B0740−28 (Jones et al. 2002). Out of above one thousand radio pulsars known, associated bow shocks have been discovered just in very few cases. While synchrotron emission from the relativistic material in the wind seems too weak to make these nebulae detectable, the emission of optical Balmer lines (mostly Hα) is more relevant. It is the signature of a non-radiative shock moving through a partially neutral medium (Chevalier & Raymond 1980), and originates from de-excitations of neutral H atoms, following collisional excitations or exciting charge-exchange processes. It dominates the optical emission when recombination times are long, and it has been extensively studied on various supernova remnants. We have found (Bucciantini & Bandiera 2001; Bucciantini 2002) that many of the run-away pulsars should give rise to buw-shock even if only the most energetic and fast would be able to interact efficiently with the neutral component of the ISM to give a detectable flux (mainly Hα). An other interesting point is that two of the four known nebulae do not show a shape closely matching that of a classical bow shock: we have found that neutral hydrogen can penetrate the pulsar wind bubble and change the fluid structure of the nebula itself giving wider shape as observed.

The study of pulsar-wind nebulae is precious to investigate physical effects important also for other classes of sources.

Pulsar-wind nebulae are among the best sources on which to study ultrarelativistic outflows and shocks particle acceleration in relativistic shocks, and interaction of a relativistic flow with thermal matter. Although on different spatial and energy scales, pulsar-wind nebulae share similarities with other astrophysical phenomena such as AGN jets, gamma-ray bursts (GRBs), microquasars, and models of pulsar-wind nebulae could be extended to other astrophysical contexts.

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