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HIGH RESOLUTION X-RAY OBSERVATIONS OF PULSAR WINDS

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RESUMEN

Los pulsares jóvenes giran extremadamente rápido pero también se están desacelerando a una tasa muy rápida. Este proceso se lleva cantidades enormes de energía de la estrella en forma de un viento relativista. Por medio de la resolución proporcionada por el *Observatorio de Rayos X Chandra*, una multitud de observaciones nuevas de pulsares y sus vientos está demostrando la diversidad y complejidad con las que los pulsares interactúan con su medio ambiente. En este artículo revisamos nuestro entendimiento básico de los vientos de los pulsares y brevemente resumimos algunas de las nuevas ideas proporcionadas por *Chandra* acerca de la estructura de los choques, la aceleración de las partículas y la composición de los vientos.

ABSTRACT

Young pulsars spin incredibly quickly but are also slowing down at a very rapid rate. This process carries away enormous amounts of energy from the star in the form of a relativistic wind. Through the high resolution now offered by the *Chandra X-ray Observatory*, a flood of new observations of pulsars and their winds is demonstrating the diversity and complexity with which pulsars interact with their surroundings. This paper reviews our basic understanding of pulsar winds, and briefly summarizes some of the new insights provided by *Chandra* on shock structure, particle acceleration and wind composition.

Key Words: **ISM: JETS AND OUTFLOWS — STARS: NEUTRON — SUPERNOVA REMNANTS — X-RAYS: ISM**

1. INTRODUCTION

There is an enormous amount of kinetic energy associated with the rapid rotation of a young pulsar. For example, a newborn neutron star with an initial period of 5 ms has a rotational kinetic energy of $\sim 10^{51}$ erg, comparable to that released in the associated supernova explosion. Pulsar timing observations clearly demonstrate that all known isolated pulsars are slowing down, indicating that this huge reservoir of kinetic energy is being steadily dissipated. The power associated with this loss of rotational energy (the "spin-down luminosity") is

$$\dot{E} = \frac{d}{dt}\left(\frac{1}{2}I\omega^2\right) = 4\pi^2 I\frac{\dot{P}}{P^3}, \qquad (1)$$

where $P = 2\pi/\omega$ is the pulsar spin-period, and I is the star's moment of inertia (usually assumed to have the value $I \equiv 10^{45}\,\mathrm{g\,cm^2}$). For the observed range of P and $\dot{P}$, we find values up to $\dot{E} \sim 10^{39}\,\mathrm{erg\,s^{-1}}$, implying that some pulsars deposit their energy into their environment at a rate comparable to the bolometric luminosity of the most massive stars. It is thus reasonable to ask: where does all this energy go?

In most cases the luminosity of the pulsations themselves is negligible. It is rather thought that most of a pulsar's spin-down energy goes into a relativistic wind, populated with electrons, positrons, and possibly ions as well. If this wind can be confined, synchrotron emission will be generated, producing an observable *pulsar wind nebula* (PWN).

By far the most well-studied PWN is the Crab Nebula. The central pulsar in the Crab has $\dot{E} = 4 \times 10^{38}\,\mathrm{erg\,s^{-1}}$; one can independently infer that $\sim 10^{38}\,\mathrm{erg\,s^{-1}}$ must be supplied to the surrounding nebula to maintain the observed distribution of magnetic fields and particles. We conclude that the bulk of a pulsar's spin-down is deposited into its PWN, and that a PWN acts as a useful probe of a pulsar's energy loss and interaction with its surroundings.

2. PULSAR WIND NEBULAE

A simple model of pulsar wind nebulae allows one to understand their basic energetics and structure. Near the pulsar, wind particles flow freely outwards with zero pitch angle. While this region is not directly observable, we can infer from theoretical arguments that in this region the wind has a composition $\sigma \gg 1$ (e.g., Coroniti 1990), where σ is defined as the ratio of electromagnetic energy to particle energy in the wind.

At some point from the pulsar the wind will be confined by external pressure. In this region a termination shock is formed, in which particles are accelerated and synchrotron radiation is produced. At least in the case of the Crab Nebula, observations and modeling of the PWN emission allow us to de-

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termine $\sigma \approx 0.003$ at the termination shock (Kennel & Coroniti 1984; Emmering & Chevalier 1987), corresponding to a weakly magnetized wind. It is not clear where or how the wind makes an apparent transition from $\sigma \gg 1$ to $\sigma \ll 1$, a problem referred to as the "σ paradox" (Melatos 2002, and references therein). Downstream of the termination shock, the wind decelerates and the pitch angles are randomized; synchrotron emission is subsequently generated, producing an extended PWN.

Synchrotron emission is an intrinsically broadband process. However, of particular interest in the case of PWNe is emission in the X-ray band, because the synchrotron lifetimes of X-ray-emitting electrons are comparatively short (typically 1 to 10 years for typical PWN magnetic fields). This means that X-ray observations of PWNe directly trace the current conditions in the nebula and near the pulsar. However, these short lifetimes also implies that the emitting particles generally are not able to travel far from the pulsar, resulting in a comparatively small angular extent for the nebular emission. In practice, this means that previous X-ray images of PWNe, typically with a spatial resolution of an arcmin or worse, showed interesting morphologies but were unable to clearly resolve any nebular structures. Furthermore, observations in the soft part of the X-ray band suffer from significant photoelectric absorption, limiting the sensitivity of the resulting images.

Due to these limitations, X-ray studies of pulsars and their nebulae have long been a frustrating case of "blobology". It is only with the launch in 1999 of the *Chandra X-ray Observatory* that major new advances in this field are finally now being made. The main reason for this is *Chandra*'s superb subarcsecond resolution, which allows us to see structures very close to the central pulsar. The *Chandra* CCDs also have moderate spectral resolution, sufficient for spatially resolving the emitting particle distribution in these sources. Finally, *Chandra*'s coverage of the harder parts of the X-ray band (up to 10 keV) ensures that the sensitivity of the observations are not limited by absorption.

3. THE CRAB NEBULA

Not surprisingly, the Crab Nebula was the first PWN looked at by *Chandra*. The resulting image (Figure 1, Weisskopf et al. 2000; Hester et al. 2002) is nothing short of spectacular, showing a variety of features not apparent from earlier images. These include the central pulsar, a region of reduced emission around the pulsar corresponding to the unshocked wind zone, a clear turn-on of emission beyond this

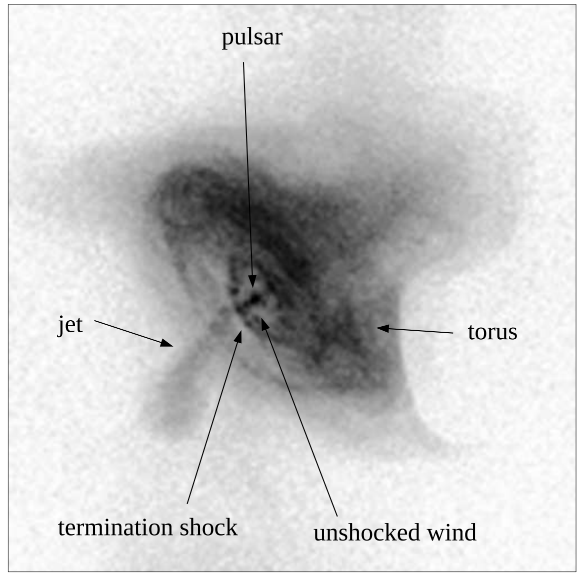

Fig. 1. *Chandra* image of the Crab Nebula (Weisskopf et al. 2002). The central pulsar has an age of 950 yrs, a spin-down luminosity $\dot{E} = 4 \times 10^{38}$ erg s^{-1} and is at a distance of 2 kpc. The image is $4' \times 4'$ in size.

zone representing the termination shock, a broad torus comprising the bulk of the nebular emission, and a fainter "jet" aligned with the axis of the torus.

The elliptical morphology of the termination shock demonstrates that the relativistic outflow from the Crab pulsar is not isotropic, but rather is focused into an equatorial flow. Within this interpretation, it seems likely that the jet of emission is directed along the pulsar spin-axis, which is the only fixed symmetry axis associated with the system.

4. PULSAR B1509–58

PSR B1509–58 is a young and energetic radio, X-ray and γ-ray pulsar. Previous observations have shown this source to be surrounded by an elongated X-ray PWN, with thermal X-rays from the associated supernova remnant G320.4−1.2 immediately to the north. *ROSAT* data have revealed a number of interesting features in this source: there is the suggestion of a collimated outflow along the pulsar spin-axis like that seen in the Crab Nebula, a possible compact disc of emission immediately surrounding the pulsar, and evidence for a "torus plus jets" morphology resembling that of the Crab (Greiveldinger et al. 1995; Brazier & Becker 1997).

We have carried out *Chandra* observations of this source to follow up on these possibilities, as reported in detail by Gaensler et al. (2002). The resulting image, presented in Figure 2, shows the pulsar itself, surrounded by a diffuse elongated nebula, with a clear jet-like structure lying to the south of the

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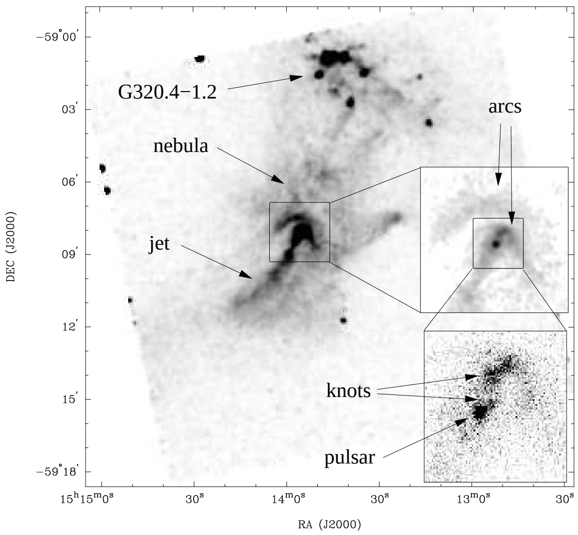

Fig. 2. *Chandra* image of PSR B1509–58 and its PWN (Gaensler et al. 2002). The central pulsar has an age of 1700 yrs, a spin-down luminosity $\dot{E} = 2 \times 10^{37}$ erg s^{-1} and is at a distance of 5 kpc. The two sub-panels show the central region at successively higher resolution.

pulsar along the main symmetry axis of the nebula. There is also an arc of emission immediately to the north of the pulsar, bisected by this symmetry axis. At higher resolution, a second arc is seen nestling inside the main arc. Even closer to the pulsar is a collection of 3 to 4 knots of X-ray emission.

The *Chandra* data demonstrate that there is a clear symmetry axis associated with this system, defined on scales ranging from $10''$ up to $10'$. As with the Crab Nebula, it is most likely that this axis represents the pulsar spin axis. The collimated, curved jet-like feature also resembles that seen for the Crab. This feature has a harder X-ray spectrum than the rest of the PWN. If this hard spectrum results from a lack of synchrotron cooling compared to surrounding emission, the more rapid rate at which particles in this region must be replenished implies a flow velocity along this feature of $> 0.2c$ (Gaensler et al. 2002). Thus it appears that this structure is indeed a true jet, which is somehow being accelerated and collimated by the pulsar.

The morphology of the arcs seen to the north of the pulsar suggest that they are circular rings in an inclined equatorial plane. Gaensler et al. (2002) have interpreted these arcs in the context of the PWN model of Gallant & Arons (1994), who argue that ions in the wind undergo magnetic reflection in the termination shock zone, and that the electrons are consequently compressed at the ion turning points. This produces synchrotron "wisps" where the electrons are compressed, whose predicted spacing ($\sim$ 1.8 to 1) match that of the two arcs seen here. The particle flux through these features allows us to calculate a magnetization parameter at the termination shock of $\sigma \approx 0.005$, comparable to that previously determined for the Crab Nebula.

Within this interpretation, the knots seen very close to the pulsar then represent emission from the *unshocked* wind, upstream of the termination shock. While the process through which these features are produced is as yet uncertain, we assume that their observed width represents a Larmor orbit of the emitting particles. The consequent magnetic field allows us to infer that $\sigma < 0.003$ at a separation from the pulsar of $\lesssim 0.1$ pc (see Gaensler et al. 2002 for details). Thus, if there is truly a transition in the wind from $\sigma \gg 1$ to $\sigma \ll 1$, it occurs much closer to the pulsar than can be resolved even with *Chandra*.

5. CONCLUSIONS

The detailed *Chandra* datasets now being obtained on these and other PWNe conclusively demonstrate that X-ray observations at high resolution give us our best insight yet into the processes through which pulsars lose their rotational energy. Fundamental similarities are now emerging amongst the wind properties of the pulsar population, but this new level of detail also makes clear that there are important (and yet to be understood) differences.

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