Discovery of an X-ray Nebula associated with PSR J2124–3358

C. Y. Hui and W. Becker

Max–Planck–Institut für extraterrestrische Physik, Giessenbachstraße, 85740 Garching, Germany

Abstract. We report the discovery of an X-ray nebula associated with the nearby millisecond pulsar PSR J2124–3358. This is the first time that extended emission from a solitary millisecond pulsar is detected. The emission extends from the pulsar to the northwest by ~ 0.5 arcmin. The spectrum of the nebular emission can be modeled by a power law spectrum with photon index of ∼ 2.2 ± 0.4. This is inline with the emission being originated from accelerated particles in the post shock flow.

1. Introduction

Rotation-powered pulsars are well-known to be the objects tapping their rotational energy into pulsed emission. However, it is now generally believed that a much larger fraction of the rotational energy leaves the pulsars’ magnetosphere in the form of magnetized wind. When the relativistic wind particles interact with the interstellar medium, synchrotron emission, which is characterized by a power-law spectrum (Chevalier 2000) is radiated.

If a pulsar moves across the surrounding medium with a velocity exceeding the speed of sound for the medium, a bow shock can be formed. The structure of a bow shock can consist of two parts (Gaensler 2005). The forward shock, resulting from collisional excitation, is expected to produce Hα emission. Also, the termination shock is produced by the pressure difference between regions ahead of and behind the pulsar’s velocity vector. The relativistic wind particles will be accelerated in the termination shock and hence generate synchrotron emission from radio to X-ray. The morphology of the X-ray termination shock is generally cometary.

Recently, we have conveyed searches for diffuse X-ray emission around a group of millisecond pulsars. The pulsars are PSR J2124–3358, J0437–4715, J0030+0451 and J1024–0719 which have comparable spin parameters (Hui & Becker 2006). The period and period derivative of this group have ranges of 4.87–5.76 ms and (1.0–1.87) × 10^{-20} s s^{-1} respectively. In this work, we have discovered an elongated structure associated with PSR J2124–3358 (Figure 1).

PSR J2124-3358 was discovered by Bailes et al. (1997) during the Parkes 436 MHz survey of the southern sky. The pulsar has a rotation period of P = 4.93 ms and a proper motion corrected period derivative of ˙P = 1.33 × 10^{-20} s s^{-1}. These spin parameters imply a characteristic age of 5.86 × 10^6 yrs and a dipole surface magnetic field of 2.60 × 10^8 G (Manchester et al. 2005). The radio dispersion measure gives a distance of about 250 kpc. It is found to have a space velocity of ~ 58 km/s (Manchester et al. 2005). Gaensler, Jones & Stappers (2002) discovered an Hα-emitting bow shock nebula around PSR J2124-3358. This bow shock is very broad and highly asymmetric about the direction of the pulsar’s proper motion.

2. Data Analysis and Results

PSR J2124–3358 has been observed by XMM-Newton in 2002 April 14–15 with an effective exposure time of ~ 40 ks. A vignetting corrected image of the field of PSR J2124-3358 as seen by the XMM-Newton’s MOS1/2 CCDs is shown in Figure 1a. The binning factor in this image is 6 arcsec. Adaptive smoothing with a Gaussian kernel of σ < 4 pixels has been applied to the image. X-ray contours are calculated and overlaid on the image. The contour lines are at the levels of (4.2, 5.2, 7.6, 13, 28, 63) × 10^{-6} cts s^{-1} arcsec^{-2}. It can be seen that the X-ray source which is coincident with the pulsar position has an asymmetric source structure of ~ 0.5 arcmin extent, with its orientation to the northwest. Systematic effects which could cause an adequate distortion of the instrument’s point spread function (PSF) are not known for XMM-Newton. We are therefore prompted to interpret this elongated structure in terms of a pulsar X-ray trail. The signal-to-noise of this elongated feature in the XMM-Newton data is ~ 4 in the energy range 0.25 – 5 keV.

We have investigated a possible contribution to the diffuse X-ray emission by nearby stars. To do so, we investigated the Digitized Sky Survey data (DSS) for the sky region around PSR J2124–3358. There are four field stars, which are labeled as A, B, C and D in Figure 1a, in the 1.5 arcmin neighborhood of PSR J2124–3358. None of them is found to match the position of the diffuse elon-
Fig. 1. a) XMM-Newton MOS1/2 image of PSR J2124−3358 with overlaid contours. The pulsar proper motion is indicated by an arrow. The position of bright stars located in the 1.5 arcmin neighborhood is indicated.
b) PSR J2124−3358 as seen by the ACIS detector aboard Chandra.

gated X-ray structure. It can be seen in Figure 1a that the positions of stars B and C coincide with two faint X-ray sources which are disconnected with the trail emission of PSR J2124−3358, though.

The detection is which supported by the Chandra ACIS-S3 observation took place on 2004 December 19-20 for an exposure time of ∼30 ks. An image made from this data with 0.5 arcsec binning and adaptive smoothing applied (using a Gaussian kernel with σ < 1.5 pixel) is shown in Figure 1b. Arc-like diffuse emission which is within the pulsar’s Hα nebula is clearly detected. Since the PSF width of XMM-Newton is about 10 times that of Chandra, it blurred most of the detailed structure seen in the Chandra data. However, it should be noted that the overall direction of the feature in the Chandra image is consistent with the orientation of the trail detected by XMM-Newton. The signal-to-noise of this feature in the Chandra data is ∼5 in the energy range of 0.3 − 8 keV.

For the spectral analysis, we extracted the energy spectrum within a 30 × 35 arcsec box from the XMM-Newton MOS1/2 data. Using a box rather than a circular selection region allows to avoid the emission from the pulsar and excludes any potential contamination from the field stars B and C. However, we estimate that the wing of the XMM-Newton PSF centered at the pulsar position still contributes ∼20% to the total counts inside the box. The background spectrum was extracted from a source free region near to PSR J2124−3358. In total, 92 and 67 source counts are available from the trail in the MOS1 and MOS2 detectors, respectively. Response files were computed by using the XMMSAS tasks RMFGEN and ARFGEN. The spectra were dynamically binned so as to have at least 10 counts per bin.

In the Chandra data we selected the energy spectrum of the diffuse emission from a box of size 10 × 20 arcsec. Owing to the narrow PSF of Chandra the contamination of pulsar emission in this box is negligible. The background spectrum was extracted from a low count region near to the diffuse feature. In total 46 source counts are contributed from the Chandra data. Response files were computed by using tools MKRMF and MKARF of CIAO. The spectrum was binned to have at least 8 counts per bin. The degradation of quantum efficiency of ACIS was corrected by applying the XSPEC model ACISABS.

We hypothesize that the diffused emission should be originated from the interaction of pulsar wind and the ISM. Synchrotron radiation from the ultra-relativistic electrons is generally believed to be the emission mechanism of the pulsar wind nebula, which then is characterized by a power-law spectrum. With a view to test this hypothesis, we fitted an absorbed power-law model to the nebular spectrum with XSPEC 11.3.1 in the 0.25 − 10
keV energy range. With a column density of $5 \times 10^{20}$ cm$^{-2}$ as obtained from spectral fits to the pulsar emission, we found that the model describes the observed spectrum fairly well ($\chi^2 = 0.79$ for 26 D.O.F.). The photon index is $\alpha = 2.2 \pm 0.4$ and the normalization at 1 keV is $(2.94 \pm 0.48) \times 10^{-6}$ photons keV$^{-1}$ cm$^{-2}$ s$^{-1}$ $(1 - \sigma$ error for 1 parameter in interest). In view of the low photon statistic we tested for a possible dependence of the fitted model parameters against the background spectrum. All deviations found in repeating the fits with different background spectra were within the $1 - \sigma$ confidence interval quoted above. The unabsorbed fluxes and luminosities deduced for the best fit model parameters and the energy ranges 0.1–2.4 keV and 0.5–10 keV are $f_X = 1.8 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, $L_X = 1.3 \times 10^{29}$ ergs s$^{-1}$ and $f_X = 1.2 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$, $L_X = 8.9 \times 10^{28}$ ergs s$^{-1}$, respectively. The best fitting spectral model is displayed in Figure 2.

3. Discussions

Adopting the dispersion measure based distance of $\sim 250$ pc, the X-ray trail has a length of $l \sim 1.1 \times 10^{17}$ cm. For the pulsar's proper motion velocity of 58 km s$^{-1}$ (Manchester et al. 2005), the timescale, $t_{\text{flow}}$, for the passage of the pulsar over the length of its X-ray trail is estimated to be $\sim 600$ yrs. According to the discussion in Becker et al. (2005) on the trail emission of PSR B1929+10 we estimate the magnetic field in the shocked region by assuming $t_{\text{flow}}$ to be comparable to the electron lifetime of the synchrotron emission. This yields $\sim 30 \mu$G for the inferred magnetic field strength in the emitting region. The magnetic field strength in the ISM is estimated to be $\sim 2 - 6 \mu$G (cf. Beck et al. 2003 and references therein). Taking into account that the magnetic field in the termination shock might be compressed (e.g. Kennel & Coroniti 1984), our estimation is approximately consistent if the compression factor is $\sim 7$.

Following Becker et al. (2005), we applied a simple one zone model (Chevalier 2000) to estimate the spectral behavior and the X-ray luminosity of the nebular emission. The X-ray luminosity and spectral index depend on the inequality between the characteristic observed frequency $\nu^{\text{obs}}_X$ and the electron synchrotron cooling frequency $\nu_c$ which is estimated to be $1.6 \times 10^{17}$ Hz. Since in general $\nu^{\text{obs}}_X > \nu_c$, we concluded that the emission is in a fast cooling regime. Electrons with the energy distribution, $N(\gamma) \propto \gamma^{-\alpha}$, are able to radiate their energy in the trail with photon index $\alpha = (p + 2)/2$. The index $p$ due to shock acceleration typically lies between 2 and 3 (cf. Cheng, Taam, & Wang 2004 and references therein). Taking $p = 2.35$ yields $\alpha^\text{th} \sim 2.2$ which is in accordance with the result from the observed value $\alpha^{\text{obs}} = 2.2 \pm 0.4$. Assuming the energy equipartition between the electron and proton (Cheng, Taam, & Wang 2004), we take the fractional energy density of electron $\epsilon_e$ to be $\sim 0.5$ and the fractional energy density of the magnetic field $\epsilon_B$ to be $\sim 0.01$. Assuming a number density of ISM to be 1 cm$^{-3}$, the distance of the shock from the pulsar is estimated to be $\sim 3.6 \times 10^{16}$ cm. With these estimates, the calculated luminosity, $\nu L_\nu$, is given as $\sim 10^{29}$ ergs s$^{-1}$ which is well consistent with the observed values of $1.3 \times 10^{29}$ ergs s$^{-1}$ (0.1-2.4 keV) and $8.9 \times 10^{28}$ ergs s$^{-1}$ (0.5-10 keV).

Although the general properties of the X-ray trail in PSR J2124–3358 are not in contradiction with properties observed in other pulsars there are still ambiguities which are not completely resolved. First, one should notice that the trail is misaligned with the direction of the pulsar's proper motion. As reported by Gaensler, Jones, & Stappers (2002), the head of the $H_\alpha$ bow shock is found to be highly asymmetric about the pulsar’s velocity vector with the apparent nebular symmetry axis deviated from the velocity vector by $\sim 30^\circ$. Even though the misalignment of the X-ray trail seems to agree with the asymmetry of the $H_\alpha$ nebula, deeper observations by XMM-Newton and Chandra are required in order to constrain the physical properties of this interesting nebula in higher detail.

Acknowledgements. We gratefully acknowledge the support by the WE-Heraeus foundation.

References

Bailes, M., Johnston, S., Bell, J. F., Lorimer, D. R., Stappers, B. W., Manchester, R. N., Lyne, A. G., Nicastro, L., D’Amico, N., & Gaensler, B. M. 1997, ApJ, 481, 386
Beck, R., Shukurov, A., Sokoloff, D., & Wielebinski, R. 2003, A&A, 411, 99
Becker, W., et al. 2006, ApJ, 645, 1421
Cheng, K. S., Taam, R. E., & Wang, W. 2004, ApJ, 617, 480
Chevalier, R.A. 2000, ApJ, 539, L45
Gaensler, B.M. 2005, AdSpR, 35, 1116
Gaensler, B. M., Jones, D. H., & Stappers, B. W. 2002, ApJ, 580, L137
Hui, C.Y., & Becker, W. 2006, A&A, 448, L13
Kennel, C. F., & Coroniti, F. V. 1984, ApJ, 283, 694
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993