PSR J0357+3205: A FAST-MOVING PULSAR WITH A VERY UNUSUAL X-RAY TRAIL

A. De Luca1,2, R. P. Mignani1,3,4, M. Marelli1, D. Salvetti1,5, N. Sartore1, A. Belﬁore6, P. Szaz Parkinson6, P. A. Caraveo1,2, and G. F. Bignami1,7

1 INAF-Istituto di Astroﬁsica Spaziale e Fisica Cosmica Milano, Via E. Bassini 15, I-20133 Milano, Italy; deluca@iasf-milano.inaf.it
2 Istituto Nazionale di Fisica Nucleare, Sezione di Pavia, Via Bassi 6, I-27100 Pavia, Italy
3 Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey RH5 6NT, UK
4 Kepler Institute of Astronomy, University of Zielona Góra, Lubuska 2, 63-265 Zielona Góra, Poland
5 Dipartimento di Fisica, Università degli Studi di Pavia, Via Bassi 6, I-27100 Pavia, Italy
6 Department of Physics, Santa Cruz Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA
7 Istituto Universitario di Studi Superiori di Pavia, Piazza della Vittoria n.15, I-27100 Pavia, Italy

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ABSTRACT

The middle-aged PSR J0357+3205 is a nearby, radio-quiet, bright γ-ray pulsar discovered by the Fermi mission. Our previous Chandra observation revealed a huge, very peculiar structure of diffuse X-ray emission originating at the pulsar position and extending for >9′ on the plane of the sky. To better understand the nature of such a nebula, we have studied the proper motion of the parent pulsar. We performed relative astrometry on Chandra images of the field spanning a time baseline of 2.2 yr, unveiling a significant angular displacement of the pulsar counterpart, corresponding to a proper motion of 0′.165 ± 0′.030 yr−1 at a position angle (P.A.) of 314° ± 8°. At a distance of ∼500 pc, the space velocity of the pulsar would be of ∼390 km s−1 assuming no inclination with respect to the plane of the sky. The direction of the pulsar proper motion is aligned very well with the main axis of the X-ray nebula (P.A. = 315.5 ± 1.5), pointing to a physical, yet elusive, link between the nebula and the pulsar space velocity. No optical emission in the Hα line is seen in a deep image collected at the Gemini telescope, which implies that the interstellar medium into which the pulsar is moving is fully ionized.

Key words: pulsars: general – pulsars: individual (PSR J0357+3205) – stars: neutron

Online-only material: color figures

1. INTRODUCTION

The Large Area Telescope on board the Fermi satellite (Fermi-LAT; Atwood et al. 2009) has opened a new era for pulsar astronomy by detecting γ-ray pulsations (at E > 100 MeV) from more than 120 pulsars,8 about 30% of which are not detected at radio wavelengths. The middle-aged PSR J0357+3205 (characteristic age τc ∼ 0.54 Myr, P ∼ 444 ms, surface B-field ∼2.3 × 1012 G) is one of the most interesting radio-quiet pulsars discovered in blind radio surveys in Fermi-LAT data (Abdo et al. 2009a). Its high γ-ray ﬂux (it is included in the Fermi-LAT bright source list; Abdo et al. 2009b), low spin-down luminosity (Edot = 5 × 1033 erg s−1), and off-plane position (Galactic latitude b ∼ −16°) point to a small distance of about 500 pc. A joint X-ray and optical program with Chandra and the NOAO Mayall 4 m telescope at Kitt Peak allowed us to identify the soft X-ray counterpart of the pulsar as well as to discover the existence of a very large, elongated feature of diffuse X-ray emission, apparently originating at the pulsar position and extending for more than 9′ (corresponding to ∼1.3 pc at the distance of 500 pc, assuming no inclination with respect to the plane of the sky), with a hard spectrum consistent both with a power law and with a hot thermal bremsstrahlung (De Luca et al. 2011).

Elongated “tails” of diffuse emission have been associated with several rotation-powered pulsars (e.g., Kargaltsev & Pavlov 2008) and explained as “velocity-driven” bow-shock pulsar wind nebulae (see Gaensler & Slane 2006 for review). If a pulsar moves supersonically through the interstellar medium (ISM), the termination shock of the pulsar wind assumes a “bullet” morphology, due to ram pressure. Particles accelerated at the shock emit synchrotron radiation and cool down, confined by ram pressure in an elongated region aligned with the pulsar space velocity. However, explaining the nature of the nebula associated with PSR J0357+3205 turned out to be very challenging. As discussed by De Luca et al. (2011), the standard picture cannot apply here since the morphology is very different from the “cometary” shape which characterizes all other X-ray bow-shock nebulae. There is no emission in the surroundings of the pulsar, where the brightest portion (the termination shock) should be—indeed, the surface brightness grows as a function of the distance from PSR J0357+3205. Moreover, there is no evidence for spectral evolution as a function of the position, at odds with expectations for a population of particles injected at the shock and cooling via synchrotron radiation.

Other pictures could be explored. For instance, PSR B2224+65, the fast-moving pulsar powering the well-known “Guitar nebula” seen in Hα (Cordes et al. 1993), displays an elongated X-ray feature that is reminiscent of the one of our target and cannot be a bow-shock nebula because it is misaligned by ∼118° with respect to the direction of the proper motion (Hui & Becker 2007). Thus, the possibility of a ballistic jet (similar to active galactic nuclei) or the hypothesis of a nebula confined by a pre-existing, large-scale magnetic field in the ISM has been proposed (Bandiera 2008; Johnson & Wang 2010; Hui et al. 2012).

Indeed, a crucial piece of information in order to understand the physics of the huge elongated feature associated with PSR J0357+3205 is the direction of the pulsar proper motion.
Detecting a pulsar angular displacement aligned with the nebula’s main axis would point to a link between the morphology of the diffuse structure and the pulsar velocity. Conversely, if it were misaligned, the case of PSR J0357+3205 would become very similar to the one of PSR B2224+65 and would require a different explanation for the nature of the nebula.

Usually, a pulsar proper motion is measured in the radio band, or, more rarely, in the optical domain. Unfortunately, our target is radio quiet and has no optical counterpart; moreover, timing analysis of gamma-ray photons is not particularly sensitive to the proper motion (positional accuracy based on 5 yr of Fermi-LAT timing is estimated to be ~2\(^{\prime}\); Ray et al. 2011). The only way to search for a possible proper motion rests on the comparison of multi-epoch, high-resolution X-ray images. To this aim, we have obtained a multi-cycle observing campaign with Chandra, consisting of two observations to be performed at the end of 2011 and at the end of 2013. We will report here on the first observation of our program as well as on a very recent observation of the field in the H\(\alpha\) band performed with Gemini Multi-Object Spectrograph (GMOS) instrument at the Gemini North Telescope. Indeed, pulsars moving supersonically into warm interstellar gas can generate optical emission in the H\(\alpha\) line, due to collisional excitation of neutral hydrogen and charge exchange occurring at (and behind) the forward shock (see, e.g., Cordes et al. 1993), yielding a limb-brightened, arc-shaped bow-shock nebula, located at the apex of the forward shock, in the direction of the proper motion.

2. MEASUREMENT OF THE PULSAR PROPER MOTION

The superb angular resolution of the Chandra optics makes it possible to measure tiny angular displacements of an X-ray source by performing relative astrometry on multi-epoch images. Indeed, such an approach has already been used to measure the proper motion of a few isolated neutron stars. See, e.g., our investigation for the case of SGR 1900+14 (De Luca et al. 2009) as well as the work by Motch et al. (2007, 2008), Kaplan et al. (2009), Becker et al. (2012), and van Etten et al. (2012).

2.1. Chandra Observations and Data Reduction

Our new observation of PSR J0357+3205 with Chandra was performed on 2011 December 24 (ObsID 14007, 29.4 ks exposure time—hereafter tagged as “2011”). Previous observations were performed on 2009 October 25 (ObsID 12008, 29.5 ks—hereafter “2009a”) and on 2009 October 26 (ObsID 11239, 47.1 ks—hereafter “2009b”). All data were collected using the Advanced CCD Imaging Spectrometer (ACIS) instrument in timed exposure mode with the WAVFIAT telemetry mode. We retrieved “Level 1” data from the Chandra Science Archive and reprocessed them with the chandra_repro\(^9\) script of the Chandra Interactive Analysis of Observation Software (CIAO v4.4)\(^10\).

For each observation, we generated an image in the 0.3–8 keV energy range using the original ACIS pixel size (0.492 pixel \(^{-1}\)). We performed a source detection using the wavdetect\(^11\) task with wavelet scales ranging from 1 to 16 pixels with a \(\sqrt{2}\) step size, setting a detection threshold of \(10^{-8}\). In all observations, the target was imaged close to the aimpoint, on the backside-illuminated chip S3 of the ACIS-S array.

We cross-correlated the resulting source lists using a correlation radius of 3\(^{\prime}\) and we extracted a catalog of common sources for each pair of observations. In view of the density of sources in each image, the possibility of a chance alignment of two false detections is \(<10^{-5}\). As a further step, we selected sources within 4\(^{\prime}\) of the aimpoint since the telescope point spread function deteriorates as a function of off-axis angle, hampering source localization accuracy (see discussion in De Luca et al. 2009). Such an exercise yielded 12 common sources (2011 versus 2009a), 10 sources (2011 versus 2009b), and 16 sources (2009a versus 2009b), in addition to the target pulsar. The uncertainty on the source localization on each image depends on the signal to noise as well as on the off-axis angle and, following the estimates by the wavdetect task, it ranges from \(-0.08\) to \(-0.7\) pixel per coordinate. We note that using the empirical formula for the positional error of ACIS sources derived by Kim et al. (2007) yields very similar (or slightly smaller) uncertainties for our target as well as for our reference sources located very close to the aimpoint.

2.2. Relative Astrometry

The positions of the selected common sources (excluding the pulsar counterpart) were adopted as a reference grid to perform relative astrometry. We used the ACIS SKY reference system\(^12\) (pixel coordinates with axes aligned along right ascension (R.A.) and declination (decl.)). Taking into account the corresponding uncertainties, we computed the best geometric transformation needed to superimpose the reference frames of two images collected at different epochs.

We superimposed the first-epoch 2009a and (separately) 2009b data to the most recent 2011 data in order to measure the possible pulsar displacement over a baseline of \(\sim 2.2\) yr. We also superimposed 2009a data to 2009b data (no displacement is expected on a 1 day baseline) in order to check for systematics affecting our analysis. A simple translation yielded a good superposition in all cases (see Table 1). The uncertainty on the frame registration turned out to be smaller than 50 mas per coordinate. Adding a further free parameter to the transformation (a rotation angle) did not result in a statistically compelling improvement of the fit.

We applied the best-fit transformation to the coordinates of the pulsar counterpart and we computed its displacement between different epochs. The error budget for the overall pulsar displacement includes the uncertainty on the pulsar position in each image as well as the uncertainty on the multi-epoch frame registration. Results are shown in Table 1. Displacement of the pulsar as well as residuals on the positions of the reference sources after frame registration are also shown in Figure 1. A significant and consistent displacement of the pulsar is apparent both in the 2011 versus 2009a and in the 2011 versus 2009b comparison, while no displacement is seen for the pulsar in the 2009a versus 2009b one.

Using the relative positions of the pulsar in the 2011 frame, we computed a best-fit proper motion \(\mu_{\alpha} \cos(\delta) = 117 \pm 20\) mas yr\(^{-1}\) and \(\mu_{\delta} = 115 \pm 20\) mas yr\(^{-1}\). This corresponds to a total proper motion of \(165 \pm 30\) mas yr\(^{-1}\) translating to a (projected) space velocity of \(\sim 390 \, d_{500}\) km s\(^{-1}\) (where \(d_{500}\) is the distance to the pulsar in units of 500 pc). The position angle (P.A.) of the proper motion is \(314^\circ \pm 8^\circ\) (north to east; see Figure 2).

\(^9\) http://cxc.harvard.edu/ciao/ahelp/chandra_repro.html
\(^10\) http://cxc.harvard.edu/ciao/index.html
\(^11\) http://cxc.harvard.edu/ciao/threads/wavdetect/
\(^12\) http://cxc.harvard.edu/ciao/ahelp/coords.html
### Table 1
Results of X-Ray Relative Astrometry

|                  | 2011 vs. 2009a | 2011 vs. 2009b | 2009a vs. 2009b |
|------------------|----------------|---------------|----------------|
| Time baseline    | 2.16 yr        | 2.16 yr       | 1 day          |
| Number of reference sources | 11a            | 10            | 16             |
| Uncertainty on $X$ shift (pixels) | 0.09           | 0.08          | 0.06           |
| $\chi^2$ (dof)   | 13.6 (10)      | 15.6 (9)      | 7.8 (15)       |
| Uncertainty on $Y$ shift (pixels) | 0.08           | 0.07          | 0.06           |
| $\chi^2$ (dof)   | 8.1 (10)       | 13.0 (9)      | 13.8 (15)      |
| PSR X displacement (pixels) | 0.53 ± 0.12    | 0.50 ± 0.11   | 0.10 ± 0.10    |
| PSR Y displacement (pixels) | 0.54 ± 0.11    | 0.50 ± 0.10   | 0.04 ± 0.10    |

**Note.** a A reference source yielding high residuals was rejected.

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### 2.3. The Position Angle of the Nebula

In order to measure the sky orientation of the main axis of the nebula, we selected nine contiguous rectangular image slices (see Figure 2, inset), aligned along R.A. and decl., having a width of 25”–40” along R.A. and a height of 8:5 along decl. (excluding the two bright sources located close to the southeastern end of the nebula). For each slice, we extracted the image brightness profile in the north–south direction and, fitting a Gaussian+constant function to such profile, we evaluated the centroid of the nebular emission. A linear function describes very well ($\chi^2 = 7.5, 7$ dof) the nine resulting positions in the R.A.–decl. plane, yielding a P.A. of 315° ± 1°5 (see Figure 2). Repeating the exercise using nine image slices oriented from east to west yields fully consistent results. Thus, the proper motion direction (P.A. = 314° ± 8°) is very well aligned with the main axis of the nebula, which is indeed an “X-ray trail.”

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### 3. GEMINI Hα OBSERVATIONS

We observed the field of PSR J0357+3205 in the Hα band on 2012 September 23 with the Gemini North Telescope on the Mauna Kea Observatory, using the GMOS in its imaging mode, equipped with the interim upgrade e2v deep depletion detector (an array of three chips with unbinned pixel size of 0”072 and unvignetted field-of-view of 5:5 × 5:5). We used the Hα_G0310 filter ($\lambda = 656$ nm; $\Delta\lambda = 7$ nm), centered on the Hα rest wavelength. Observations were performed with an average airmass of 1.24, image quality of $\sim 0”8$, and gray time. Two sets of six 500 s exposures (dithered in steps of ±5 pixels) were obtained for a total integration time of 6000 s.

We processed the GMOS images with the dedicated GMOS image reduction package available in IRAF using the closest bias and sky flat-field frames from the Gemini science archive.13 From the reduced science images, we produced a mosaic of the three GMOS chips using the task gmosaic and we used the task imcoadd to average-stack the reduced image mosaics and filter out cosmic-ray hits.

We computed the astrometry calibration with the wcstools14 suite of programs, identifying on our image a set of stars from the Two Micron All Sky Survey (2MASS) All Sky Catalog of Point Sources (Skrutskie et al. 2006). We ended with an overall accuracy of $\sim 0”22$ on our absolute astrometry. Unfortunately, no observations of spectrophotometric standards stars were available for the flux calibration of our Hα image. Thus, we cross-correlated instrumental magnitudes of

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13 [http://cadcwww.dao.nrc.ca/gsa/](http://cadcwww.dao.nrc.ca/gsa/)
14 [http://tdc-www.harvard.edu/wcstools/](http://tdc-www.harvard.edu/wcstools/)
more than 150 non-saturated stars in the Gemini image to their $R_F$ magnitudes listed in the Guide Star Catalogue v2.3.2 (GSC2; Lasker et al. 2008), which yielded a rather good fit with an rms of 0.16 mag. To assess the GSC2 flux zero point, we cross-correlated the GSC2 $R_F$ magnitude of more than 500 stars with their $R$ magnitudes as tabulated in the Stetson Standard photometric star archive. We evaluated the transformation as $R_F = 0.97R - 0.32$ ($\chi^2 = 617$, 520 dof). Then, we computed the H$\alpha$ fluxes of the 150 selected stars on our Gemini image using specific fluxes corresponding to their $R_F$ magnitudes and assuming a flat spectrum within the $R$ filter bandpass. This yielded a flux calibration of the H$\alpha$ image with an uncertainty of $\sim 0.2$ mag.

No structures of diffuse emission unambiguously related to the fast motion of PSR J0357+3205 can be discerned on our Gemini image (see Figure 3). Considering a region of 10 square arcsec as a reference and taking into account the background properties of the region surrounding the pulsar position and the uncertainty in the flux calibration of our H$\alpha$ image, we computed the 5$\sigma$ upper limit to the surface brightness of an unseen bow-shock nebula to be of $5 \times 10^{-18}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$.

4. DISCUSSION

Relative astrometry on our multi-epoch Chandra images unveiled a significant proper motion of $165 \pm 30$ mas yr$^{-1}$ for PSR J0357+3205, corresponding to a velocity of $390 \pm 60$ km s$^{-1}$, along a direction almost coincident with the main axis of the elongated X-ray nebula.

Although the uncertainties of the pulsar proper motion vector and nebular main axis yield a $\sim 8\%$ chance alignment probability, our result suggests a direct link between the nebula morphology (and physics) and the space velocity of the pulsar—supersonic for any reasonable condition of the ISM (typical values of the sound speed in the ISM are of $\sim 1$, $\sim 10$, and $\sim 100$ km s$^{-1}$ for the cold, warm, and hot components, respectively; see, e.g., Kulkarni & Heiles 1988). Could the X-ray trail of PSR J0357+3205 be explained as a bow-shock PWN? While the lack of any apparent pulsar wind termination shock
could be accounted for tuning the inclination of the pulsar velocity with respect to the plane of the sky, the pulsar distance, as well as the ISM density.\footnote{Our measure of the proper motion allows us to rewrite the expected angular separation between the pulsar and the forward and backward termination shock as \( \theta_F = 0.3 d_{500} \cos^2(i) n_{1, \text{ISM}} \) and \( \theta_B = 2 d_{500} \cos^2(i) n_{1, \text{ISM}} \), respectively, where \( d_{500} \) is the distance in units of 500 pc, \( n_{1, \text{ISM}} \) is the density of the interstellar medium in units of 1 particle cm\(^{-3}\), and \( i \) is the inclination of the pulsar velocity with respect to the plane of the sky (see De Luca et al. 2011). Thus, with some reasonable tuning of such parameters, the termination shock could be unresolved from the pulsar emission \( \theta_{F, B} < 0.5^\circ \).} Other peculiarities of the trail phenomenology cannot be accounted for in the standard scenario of synchrotron emission from shocked pulsar wind. One should explain why the maximum luminosity is generated at a distance as large as \( \sim 3 \) light years from the parent neutron star. This would require an increase in the density of the radiating particles on the same distance scale (possibly due to deceleration of the bulk flow?), or an increase in the magnetic field intensity, or a change of the angle between the magnetic field and the particle flow. Moreover, the lack of any spectral steepening would require an increase in the density of the radiating particles on the same distance scale (possibly due to deceleration or re-acceleration? or large-scale organization of the flow magnetic field?) or the nature of the nebula is different (but linked to the pulsar velocity). For instance, Marelli et al. (2013) propose that the trail could be due to thermal emission by the ISM heated by the shock driven by the fast-moving pulsar.

The measure of the pulsar space velocity can be used, together with the upper limit to the surface brightness of any undetected diffuse structure in our Gemini H\( \alpha \) image, to constrain the conditions of the medium in which PSR J0357+3205 is moving. Using the scaling law proposed by Cordes et al. (1993) and Chatterjee & Cordes (2002) for the flux of the narrow-line component of a pulsar H\( \alpha \) bow-shock nebula, we estimated that the detection of H\( \alpha \) emission can only be ascribed to a neutral fraction \( X_{\text{ISM}} < 0.01 \), i.e., the gas surrounding the pulsar is fully ionized. This is true for any reasonable value of the distance to PSR J0357+3205 (ranging from \( \sim 200 \) pc, as suggested by the non-negligible X-ray absorbing column, to \( \sim 900 \) pc, where \( \gamma \)-ray luminosity would exceed the spin-down luminosity) and in a broad range of possible space velocities for the pulsar (assuming the inclination angle with respect to the plane of the sky is \( \pm 75^\circ \) range). Thus, PSR J0357+3205 could be traveling across a region filled with ISM in the hot phase. Some contribution to the ionization of the medium from the pulsar itself is also possible.

It is interesting to note that PSR J0357+3205 is located well away from the Galactic plane (\( b \sim -16^\circ \)), and its proper motion is almost parallel to the Galactic plane (it has an inclination of \( \sim 2^\circ \) toward the plane). As done in Mignani et al. (2013), we used the proper-motion information to extrapolate back in time the trajectory of the pulsar in the Galactic potential to find possible associations with open clusters and OB associations (Dias et al. 2002; Melnik et al. 2009; de Zeeuw et al. 1999), leaving the pulsar radial velocity as a free parameter and assuming a distance of 500 pc and an age of 0.54 Myr. However, we found no association with clusters or OB associations closer than \( \sim 2 \) kpc. In any case, such an exercise showed us that if PSR J0357+3205 has a radial velocity of order 600 km s\(^{-1}\) (or greater) in the direction away from the solar system, the pulsar could have been born on the Galactic plane (assuming a scale height of 60 pc, typical for massive stars; see, e.g., Maiz-Apellaniz 2001). Thus, the hypothesis of a runaway high-mass star as the progenitor of PSR J0357+3205, suggested by De Luca et al. (2011), is not required in a range of possible orbital solutions. We note that assuming a radial velocity of \( \sim 600 \) km s\(^{-1}\) would yield a total space velocity of \( \sim 715 \) km s\(^{-1}\) at the high end of the distribution of pulsar velocities derived by Hobbs et al. (2005). A very high space velocity would not change our conclusions about the elusive nature of the trail of PSR J0357+3205.

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