Radio Proper Motions of the Energetic Pulsar PSR J1813–1749

Sergio A. Dzib and Luis F. Rodríguez

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany; sdzib@mpifr-bonn.mpg.de
2 Instituto de Radioastronomía y Astrofísica, Universidad Nacional Autónoma de México, Morelia, Michoacán 58089, Mexico
3 Mesoamerican Centre for Theoretical Physics, Universidad Autónoma de Chiapas, Tuxtla Gutiérrez, Chiapas 29050, Mexico

Received 2021 September 14; revised 2021 October 17; accepted 2021 October 18; published 2021 December 24

Abstract

PSR J1813–1749 has peculiarities that make it a very interesting object of study. It is one of the most energetic and the most scattered pulsars known. It is associated with HESS J1813–178, one of the brightest and most compact TeV sources in the sky. Recently, Ho et al. used archival X-ray Chandra observations separated by more than 10 yr and determined that the total proper motion of PSR J1813–1749 is \(\sim 66\) mas yr\(^{-1}\), corresponding to a velocity of \(\sim 1900\) km s\(^{-1}\) for a distance of 6.2 kpc. These results would imply that this pulsar is the fastest neutron star known in the Galaxy and, by estimating the angular separation with respect to the center of the associated supernova remnant, has an age of only \(\sim 300\) yr, making it one of the youngest pulsars known. Using archival high angular resolution VLA observations taken over 12 yr we have estimated the radio proper motions of PSR J1813–1748 to be much smaller: \((\mu_\ell, \cos(\delta), \mu_\delta) = (-5.0 \pm 3.7, -13.2 \pm 6.7)\) mas yr\(^{-1}\), or a total proper motion of \(14.8 \pm 5.9\) mas yr\(^{-1}\). The positions referenced against quasars make our results reliable. We conclude that PSR J1813–1749 is not a very fast moving source. Its kinematic age using the new total proper motion is \(\sim 1350\) yr. This age is consistent within a factor of a few with the characteristic age of the pulsar and with the age estimated from the broadband spectral energy distribution of HESS J1813–178, as well as the age of the associated supernova remnant.

Unified Astronomy Thesaurus concepts: Radio pulsars (1353); Supernova remnants (1667); Non-thermal radiation sources (1119)

1. Introduction

PSR J1813–1749 (CXOU J181335.1–174957) is the most scattered and the second most energetic pulsar in the Milky Way (Halpern et al. 2012; Camilo et al. 2021). First discovered and characterized using Chandra X-ray observations (Gotthelf & Halpern 2009; Halpern et al. 2012), it has a spin-down rate of \(P = 1.265 \times 10^{-13}\) s yr\(^{-1}\), corresponding to a spin-down luminosity of \(\dot{E} = 5.6 \times 10^{37}\) erg s\(^{-1}\), values only below those measured for the Crab pulsar (e.g., Halpern et al. 2012).

First attempts to detect the radio pulsed emission at low frequencies (1–2 GHz) from this pulsar failed (Helfand et al. 2007; Halpern et al. 2012; Dzib et al. 2018). Recently, Camilo et al. (2021) finally detected the pulsed radio emission at higher frequencies (4–10 GHz) and showed that the pulses are highly scattered. The fact that the scattering is more severe at lower frequencies probably explains the early failed attempts to detect the radio pulsed emission. Camilo et al. (2021) show that the pulsed emission is consistent with the radio continuum source detected by Dzib et al. (2010) and Dzib et al. (2018) with the Karl G. Jansky Very Large Array (VLA) at similar frequencies. Based on the high column density at X-rays and the large dispersion measure, Camilo et al. (2021) also place a lower limit to its distance of 6.2 kpc, that could be as large as 12 kpc.

The young and relatively compact (\(\sim 2^\prime\) diameter) shell-type radio supernova remnant (SNR) G12.82–0.02 (Brogan et al. 2005) and pulsar wind nebula (PWN) observed at X-rays (Funk et al. 2007; Helfand et al. 2007; Gotthelf & Halpern 2009) have been associated to PSR J1813–1749. SNR G12.82–0.02 and the PWN are associated with one of the brightest and most compact objects discovered by the HESS Galactic Plane Survey (Aharonian et al. 2005), the TeV source HESS J1813–178. This HESS source has been associated with continuum high-energy emission from X-rays to gamma rays (Ubertini et al. 2005; Albert et al. 2006; Reimer et al. 2008; Abdo et al. 2009).

Recently, using archival X-ray observations, Ho et al. (2020) determined large proper motions for PSR J1813–1749 of \((\mu_\ell, \cos(\delta), \mu_\delta) = (-64 \pm 9, -14 \pm 7)\) mas yr\(^{-1}\). As the pulsar is at an angular distance of \(\sim 20^\circ\) from the center of the SNR G12.82–0.02 the large proper motions would indicate a young age of around 300 yr, making it one of the youngest pulsars known. This age, while consistent at the lower end of the age range of 285–2500 yr for SNR G12.82–0.02 (Brogan et al. 2005), is, however, in conflict with the age estimated for HESS J1813–178 of 2500 yr (Zhu et al. 2018) and the characteristic age of the pulsar of 5600 yr (Halpern et al. 2012). As discussed by Camilo et al. (2021), the total proper motion of \(\sim 66\) mas yr\(^{-1}\) would imply a tangential velocity of the order of 2000 km s\(^{-1}\) at 6.2 kpc, the lower limit of the distance. This velocity is larger than that of any well-measured velocity for a neutron star (see Deller et al. 2019). The total proper motion of PSR J1814–1749 is an interesting subject to study, and in this paper we present the proper motions measured with archival high angular resolution observations taken with the VLA by us and by other groups.

2. VLA Observations

For our astrometric study we looked for VLA observations with high angular resolution. The VLA provides the finest angular resolution in its most extended configurations A and B. We also restricted our search to the C band (4–8 GHz) and X band (8–12 GHz), which provide the best sensitivity, and
where PSR J1813−1749 has been previously detected. For the best astrometry it is also recommended that the observations are phase referenced to the same quasar (gain calibrator), as this provides nearly absolute astrometry.

We found two observational campaigns with all the above criteria and where the target source has been detected. These observations have been previously reported by Dzib et al. (2010) and Dzib et al. (2018). The first is one observation done in 2006 with the historical VLA at 4.86 GHz, using the A configuration, under project AL673. The second, includes a series of 12 observations, 5 centered at a main frequency of 6.0 GHz and 7 at 10.0 GHz that were made as part of project 17B-028. The observations were done in the B configuration covering the period from 2017 September to 2018 February. We also found a third observational campaign done in 2012 October under project 12B-278, at the mean frequency of 9.0 GHz, using the VLA in its A configuration. However, this third campaign used a different gain calibrator. In Section 2.1 we discuss how we corrected for this limitation. All observations were calibrated and imaged using the CASA software. Positions were determined from the image using the CASA task imfit. Fluxes and other emission properties were already given and discussed by Dzib et al. (2010) and Dzib et al. (2018), and in this work we focus on the astrometry. Basic properties of the image and position of the target source over time are listed in Table 1 and examples of the maps are shown in Figure 1.

### 2.1. Astrometric Correction for the 2012 Observations

The observations of 2006 and 2017−18 were made with the same gain calibrator (J1811−2055). This typically assures an astrometric precision of order $\approx 0.01$ for the case of observations made at centimeter wavelengths in the A configuration (Boboltz et al. 2007; Perreault 2019). We can estimate from our data the expected precision as follows. We will use the 10 determinations of position given in Table 1 for the epochs between 2017 December 11 and 2018 February 4. Over this brief period of time we do not expect significant proper motions. The positional error scales linearly with the angular size of the synthesized beam. Since all these observations were made in the B configuration we expect positional errors about three times larger than in A configuration, that is, about 30 mas. Furthermore, since this is a southern source, we expect the beam size to be about twice bigger in decl. that in R.A.

![Figure 1. Background: VLA image of PSR J1813−1749 as observed in February 2006. Contours: PSR J1813−1749 as observed in 2017 December at X band. Contour levels are $-3$, $3$, $6$, and $9$ times $7$ μJy beam$^{-1}$, the noise level on this epoch. The blue ellipse indicates the expected position of the radio source in 2017 December, following the proper motion measured by Ho et al. (2020); the ellipse semimajor axis sizes consider the propagated errors.](image-url)
configuration in band X (8.0–10.0 GHz), with 16 spectral windows of 128 MHz width each.

The final images of the two epochs of project 12B-278 and the 5 C-band epochs of project 17B-028 were compared. In addition to the source associated with PSR J1813–1749 we found five compact sources in common that are also detected in the Gaia survey (Gaia Collaboration et al. 2016, 2021). The highly accurate Gaia positions and proper motions of these five sources are given in Table 2. We corrected the radio positions of these sources with the Gaia proper motions and used them to determine a systematic offset between the positions obtained in the 17B-028 and 12B-278 projects. This offset (17B-028–12B-78) is \( \Delta \text{R.A.} = 0^\circ 0110 \pm 0^\circ 0091 \); \( \Delta \text{decl.} = -0^\circ 035 \pm 0^\circ 125 \). After adding this offset to the positions of the 12B–278 project, we obtain a final position for PSR J1813–1749 at this epoch:

\[
\begin{align*}
\text{R.A.}(J2000) &= 18^h13^m35^s180 \pm 0^s009; \\
\text{Decl.}(J2000) &= -17^\circ 49^\prime 57^\prime 52^\prime \pm 0^\prime 13.
\end{align*}
\]

We note that the error in the final position is dominated by the offset correction applied.

### 3. Results

We have performed linear least square fits to the positions of PSR J1813–1749, listed in Table 1, to determine its proper motions. The values obtained are \( (\mu_\alpha \cdot \cos \delta, \mu_\delta) = (-5.0 \pm 3.7, -13.2 \pm 6.7) \text{ mas yr}^{-1} \). The positions of PSR 1813–1749 as a function of time, and the best fit to its motion are shown in Figure 2.

### 4. Discussion and Conclusions

The proper motions of PSR J1813–1749 determined from the X-ray observations are \( (\mu_{\alpha, \text{x-rays}} \cdot \cos \delta, \mu_{\delta, \text{x-rays}}) = (-64 \pm 9, -14 \pm 7) \text{ mas yr}^{-1} \). By comparing them with our results, we clearly notice a difference in the R.A. being at radio significantly smaller. Proper motions measured at radio have a major advantage over the X-ray measurements, that is, that the positions are registered against highly accurate positions measured for quasars. The observations presented in this work also have a somewhat larger time baseline, 12 yr, than that of the X-ray observations presented by Ho et al. (2020) of 10 yr. This difference does not seem too significant, but it should be emphasized that the accuracy of proper motion determinations improves as the time interval to the 3/2 power (Dzib et al. 2017). The motions reported at X-rays would be evident, between the first and last radio observations, in position offsets.
of $-0\degree.80 = 0\degree.05$ and $-0\degree.17$ in R.A. and decl., respectively. The offset in R.A. is clearly not present, see also Figure 1.

The large proper motion has also been questioned given the strong implications for the nature of the pulsar since it implies a young kinematic age and a fast tangential velocity larger than any other known pulsar (see also the discussion by Camilo et al. 2021).

Both radio and X-ray emission are tracing the pulsar itself or material very close to it. However, given the discussion above, the measured motions at radio frequencies appear to be more reliable. We believe that most of the position shift in the X-ray image could be due to a change in the brightness structure of the PWN very near the pulsar, a possibility mentioned by Ho et al. (2020). Such structure changes have been observed in the Crab pulsar nebula (Weisskopf et al. 2011).

The total proper motion of PSR J1813−1749 from the radio is $14.8 \pm 5.9$ mas yr$^{-1}$. The lower limit of the distance to PSR J1813−1749 is 6.2 kpc and can be as large as 12.0 kpc. Then, the tangential velocity ranges from $435 \pm 174$ km s$^{-1}$ to $842 \pm 336$ km s$^{-1}$. These velocities are in the range of velocities estimated for other pulsars (i.e., Deller et al. 2019). It should be noted that the error in the proper motion is large enough to accept a stationary pulsar as a possible solution.

As noted by Ho et al. (2020), PSR J1813−1749 is offset about $20''$ from the center of the SNR G12.82−0.02 (see also Figure 1 in Dzib et al. 2018). To reach this shift the kinematic age of the pulsar is $1351^{+896}_{-385}$ yr. This age discards that this is a very young pulsar and it is in better agreement with the ages estimated for the pulsar of 5600 yr (Halpern et al. 2012) and for HESS J1813−178 of 2500 yr (Zhu et al. 2018) and for SNR G12.82−0.02 (Brogan et al. 2005).

To calculate the kinematic age we have assumed that the original position of the exploding star was at the geometric center of the SNR. However, some SNRs have shown nonuniform expansion (e.g., Borkowski et al. 2014) and the geometric center of the present-day structure does not necessarily coincide with the center of the explosion.

VLA observations have proven to be an excellent tool to determine proper motions, and, in the case of PSR J1813−1749, are at the moment the best option. Even VLBI observations will have difficulties measuring a value for this source. The angular size of the radio source is estimated to be $0''034$ (Camilo et al. 2021) due to broadening from plasma scattering. The angular resolution of VLBA observations at 5 GHz is $\sim0''004$, so the source will be resolved. The total flux density of the source is $\sim100$ $\mu$Jy (Dzib et al. 2018); if resolved very little flux density will fall in a synthesized beam and the emission will be hard to detect with standard VLBA observations. Furthermore, astrometry of resolved sources is problematic. To better constrain the proper motion of PSR J1813−1749, future VLA observations, as those presented here, will be required.

We thank an anonymous referee for valuable comments. L.F. R. acknowledges the financial support of DGAPA, UNAM (project IN108920), and CONACyT, México. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

Facility: VLA.
Software: CASA (McMullin et al. 2007).

ORCID iDs
Sergio A. Dzib @ https://orcid.org/0000-0001-6010-6200
Luís F. Rodríguez @ https://orcid.org/0000-0003-2737-5681

References
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJS, 183, 46
Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005, Sci, 307, 1938
Albert, J., Aliu, E., Anderhub, H., et al. 2006, ApJL, 637, L41
Boboltz, D. A., Fey, A. L., Psaltis, W. K., et al. 2007, AJ, 133, 906
Borkowski, K. J., Reynolds, S. P., Green, D. A., et al. 2014, ApJL, 790, L18
Brogan, C. L., Gaensler, B. M., Gelfand, J. D., et al. 2005, ApJL, 629, L105
Camilo, F., Ransom, S. M., Halpern, J. P., & Roshi, D. A. 2021, ApJ, 917, 67
Deller, A. T., Goss, W. M., Bock, J. J., et al. 2005, ApJ, 629, L105
Dzib, S., Loinard, L., & Rodríguez, L. F. 2010, RMxAA, 46, 153
Dzib, S. A., Loinard, L., Rodríguez, L. F., et al. 2017, ApJ, 834, 139
Dzib, S. A., Rodríguez, L. F., Karuppusamy, R., Loinard, L., & Medina, S.-N. X. 2018, ApJ, 866, 100
Funk, S., Hinton, J. A., Moriguchi, Y., et al. 2007, A&A, 470, 249
Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2020, A&A, 649, A1
Gaia Collaboration, Prusti, T., de Bruijne, J. H. J., et al. 2016, A&A, 595, A1
Gotthelf, E. V., & Halpern, J. P. 2009, ApJL, 700, L158
Halpern, J. P., Gotthelf, E. V., & Camilo, F. 2012, ApJL, 753, L14
Helfand, D. J., Gotthelf, E. V., Halpern, J. P., et al. 2007, ApJ, 665, 1297
Ho, W. C. G., Guillot, S., Szaj Parkinson, P. M., et al. 2020, MNRS, AIP, 498, 4396
McMullin, J. P., Waters, B., Schiebel, D., Young, W., & Golap, K. 2007, in ASP Conf. Ser. 376, Astronomical Data Analysis Software and Systems XVI, ed. R. A. Shaw, F. Hill, & D. J. Bell (San Francisco, CA: ASP), 127
Perreault, T. 2019, VLA Observational Status Summary, NRAO, https://science.nrao.edu/facilities/vla/docs/manuals/oss
Reimer, O., Funk, S., Hinton, J. A., et al. 2008, in AIP Conf. Proc. 1085, High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, W. Hofmann, & F. Rieger (Melville, NY: AIP), 376
Ubertini, P., Bassani, L., Malizia, A., et al. 2005, ApJL, 629, L109
Weisskopf, M. C., Tennant, A. F., Yakovlev, D. G., et al. 2011, ApJ, 743, 139
Zhu, B.-T., Zhang, L., & Fang, J. 2018, A&A, 609, A110