The Enigmatic Compact Radio Source Coincident with the Energetic X-Ray Pulsar PSR J1813–1749 and HESS J1813–178

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Abstract

New Very Large Array (VLA) detections of the variable radio continuum source VLA J181335.1–174957, associated with the energetic X-ray pulsar PSR J1813–1749 and the TeV source HESS J1813–178, are presented. The radio source has a right circular polarization of $\sim$50% and a negative spectral index of $-1.3 \pm 0.1$, which show that it is nonthermal. The radio pulses of the pulsar are not detected from additional Effelsberg observations at 1.4 GHz made within one week of a VLA detection. This result would appear to support the idea that the continuum radio emission detected with the VLA does not trace the time-averaged emission pulses, as had previously been suggested. We discuss other possible origins for the radio source, such as a pulsar wind, magnetospheric emission, and a low-mass star companion. However, observations made at higher frequencies by Camilo et al. show that the VLA source is in fact the time-averaged pulsed emission and that the detection of the pulses had not been achieved because this is the most scattered pulsar known.

Key words: ISM: individual objects (G12.82–0.02) – ISM: supernova remnants – pulsars: individual (CXOU J181335.1–174957) – techniques: interferometric

1. Introduction

PSR J1813–1749 (=CXOU J181335.1–174957) is the second most energetic pulsar in the Milky Way (Halpern et al. 2012). It was discovered and identified as a young pulsar with a spin period of 44.7 ms by Gotthelf & Halpern (2009) based on Chandra X-ray observations. Later, Halpern et al. (2012) used a few Chandra and XMM-Newton observations to determine the spin-down rate of PSR J1813–1749 to be $P' = 1.265 \times 10^{-13}$, corresponding to a spin-down luminosity of $E = 5.6 \times 10^{37}$ erg s$^{-1}$, thereby establishing it as an energetic young pulsar. These values are only below those of (Abdo et al. 2009) based on Chandra observations to show that the compact radio source being a background source is $178.5 \pm 0.1$, which is the characteristic age of $5 \times 10^5$. Thus, there is a high chance that the compact radio source is related to the pulsar and might correspond to the integrated emission of the radio waves. More recently, however, Dzib et al. (2010) did not detect the source during a multijulian radio observation on 2009 March 24, and they were the first to suggest that VLA J181335.1–174957 could be an intermittent radio pulsar. The alternative is that this low signal-to-noise detection is spurious.

In an unexpected result, Dzib et al. (2010) reported, for the first time, the detection of a compact ($\leq 0.02$) radio continuum source (named VLA J181335.1–174957) with a flux density of $180 \pm 20 \mu$Jy at 4.86 GHz and located within $0.013$ mJy and $S_{20} < 0.006$ mJy, respectively. The common explanation for the lack of radio pulses from high-energy pulsars is that the radio emission beam is narrower than those at higher energies, and thus the radio pulses miss the sightline toward Earth (Brazier & Johnston 1999; Watters & Romani 2011). However, it is also known that pulsars may be intermittent emitters, and so observations could miss the pulses if they are scheduled during periods of inactivity. However, intermittency is normally associated with pulsars of characteristic age, $\tau_c \approx 1$ Myr or older (Kramer et al. 2006; Camilo et al. 2012; Lorimer et al. 2012).

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observations to constrain the nature of the radio continuum source. In addition, we report on the results from pulsar periodicity searches carried out on the observations using the Effelsberg 100 m Radio Telescope. These observations were separated only by a week from the VLA observations, which were performed at the Effelsberg 100 m Radio Telescope. These observations were constrained to the region of the VLA J181335.1–174957, which was detected in the VLA observations.

2. Observations and Data Calibration

2.1. VLA Observations

In this paper, we use National Radio Astronomy Observatory (NRAO) archive data of three unpublished observations in the direction of PSR J1813–1749. These observations were collected at 5.5 GHz as part of the VLA projects 12A-444 and 12B-278. Additionally, we recently obtained new VLA observations at the C band (4–8 GHz) and X band (8–12 GHz) during project 17B-028. All of the observations were recorded in standard wideband continuum mode. The epochs and the observation details are listed in Table 1.

The data sets were edited, calibrated, and imaged using the Common Astronomical Software Applications package (CASA; McMullin et al. 2007). Specifically, we use the pipeline provided by the NRAO to calibrate the data. The pipeline is designed to flag strong radio frequency interference (RFI) and to apply a standard calibration to the data. Images of the Stokes I parameter were performed using the task `tclean`, with a weighting scheme intermediate between natural and uniform. Similarly, we also imaged the Stokes V parameter for most of the epochs, with the exception of the observations taken on 2012 October, since the source was located far enough from the phase center that beam squint distortion (that introduces spurious circular polarization) is expected for this epoch.

2.2. Effelsberg 100 m Observations and Pulsar Search

In addition to the VLA observations, we use the 100 m Effelsberg Telescope to search for the radio pulses at 1.4 GHz. The source was observed on 2018 February 12 over 2 × 24 minute sessions with the central pixel of a 7-beam feed. The receiver was tuned to a frequency of 1.36 GHz and it provided a usable bandwidth of 240 MHz, which was detected as two orthogonal polarizations. The coordinates for the telescope pointing were taken from Halpern et al. (2012). The 240 MHz signal was recorded as 320 MHz baseband data using the PSRIX system (Lazarus et al. 2016) and then converted to a filter-bank format with 512 channels and a time resolution of 64 μs. After cleaning intermittent RFI, the baseband data were searched for any periodic signals with a standard pulsar search software, PRESTO (Ransom 2001). The search was sensitive to a dispersion measure (DM) of 3496, which is several times the DM estimated for a distance of 4.8 kpc by both the NE2001 and YMN16 models for the Galactic electron-density (Cordes & Lazio 2002; Yao et al. 2017).

3. Results

VLA J181335.1–174957 was detected in all the VLA observations presented in Section 2, confirming the existence of the variable radio source reported by Dzib et al. (2010). In all of the observations, the radio continuum source is compact and pointlike (see Figure 1). The measured flux densities and the image properties of each epoch are presented in Table 1 and Figure 2. Other sources detected in the field of these new VLA observations are presented and briefly discussed in the Appendix. We note, in particular, that the angular resolution and sensitivity of the observation obtained on 2012 May 6 enabled the detection of the diffuse emission of SNR G12.82+0.02 (also see Figure 1).

The images in the Stokes V parameter imply that VLA J181335.1–174957 has a right circular polarization of π_c ~ 50% (column 10 in Table 1). In those epochs where the C and X bands were observed, we also calculated the spectral indices (α; S_v ∝ ν^α) between these bands; they are shown in column 9 of Table 1. The source has a negative spectral index (α = −1.3 ± 0.1), high circular polarization, and is variable. All of this clearly indicates that the radio emission of the source is nonthermal.

The 24 minute Effelsberg 100 m telescope observations were searched for radio pulsations in two ways. We folded the baseband data with the published P and P (Halpern et al. 2012) and searched this data to a DM of 3500. Young pulsars are known to undergo sudden spin-up in the rotation rate known as glitches, and this peaks for neutron stars with characteristic age,
Figure 1. Background: C-band (5.5 GHz) radio image from 2012 May 6, with the compact source VLA J181335.1–174957 located at the center of the image. Diffuse emission from supernova remnant G12.82–0.02 is detected. Contours: 1.4 GHz radio emission of this SNR (i.e., Helfand et al. 2007). This last image was obtained from the MAGPIS webpage (https://third.ucclnl.org/gps/index.html; Helfand et al. 2006).

Figure 2. VLA J181335.1–174957 flux densities, in radio continuum, at the different observed frequencies as a function of time. Values of flux densities before 2010 from Dzib et al. (2010). Upper limits in 2009 observations are in color just to distinguish the arrows.

\[ \tau_c \approx 10 \text{ kyr} \] (Espinoza et al. 2011). To rule out spin period changes owing to glitches, we carried out a full periodicity search with PRESTO, sensitive to a DM of 3496. Both these searches did not yield any pulsed radio emission with 10σ upper limits of 65 μJy for a pulsar duty cycle of 10%. These levels are comparable to the nondetections with the GBT by Halpern et al. (2012).

4. Discussion

The flux densities of VLA J181335.1–174957, presented in Table 1 and Figure 2, show that it was active from 2017 September 18 to 2018 February 4 with no strong variations. The variability coefficients for the C and X band during these epochs were 0.06 and 0.22, respectively, indicating only moderate variability. One of our new Effelsberg observations to search for pulsed emission occurs only a week later after our last VLA observation. From the mean emission flux at 10.0 GHz of \( \langle S_{10\,\text{GHz}} \rangle = 57 \pm 3 \, \mu\text{Jy} \) and the spectral index of \( (\alpha) = -1.3 \pm 0.1 \), the predicted flux density at 1.36 GHz of VLA J181335.1–174957 is 762 ± 14 μJy, which is much higher than our 10σ upper limits of 69 μJy. As the continuum source showed only moderate variability the previous five months, its detection with the VLA and nondetection with Effelsberg support the idea that the continuum radio source is not the time-averaged pulsed emission from the pulsar, as suggested by Halpern et al. (2012). This also suggests that the radio emission beam of the pulses does not point in the sightline toward the Earth. We cannot, however, discard high levels of scattering that will mainly affect low frequencies, leaving the pulsed emission undetected in the 1.4–2.0 GHz observations (F. Camilo et al. 2018, in preparation). The question still open is: what produces the observed continuum compact radio source VLA J181335.1–174957? We will now discuss some other possibilities for the origin of the radio continuum compact source.

A first hypothesis is that the radio emission comes from the pulsar wind (PW). It is thought that most of the spin-down luminosity of pulsars such as PSR J1813–1749 is dissipated via a magnetized wind populated by relativistic electrons and positrons (Rees & Gunn 1974). At distances between 0.1 and 1 pc from the pulsar, this wind produces an extended PWN (Gaensler & Slane 2006). An upper limit to the size of VLA J181335.1–174957 of \( \sim 0.5 \text{ pc} \) can be estimated from the highest angular resolution data presented earlier. At a distance of 4.8 kpc (Halpern et al. 2012) this corresponds to 2400 au (0.01 pc) and is an order of magnitude more compact than the smallest known PWNe. This means that the compact radio emission source may trace the inner parts of the PW. The PWNe are detected across the electromagnetic spectrum in synchrotron and inverse Compton emission and in optical emission lines when the PW shocks the surrounding medium (Gaensler & Slane 2006). In contrast, there is scarce observational or theoretical information and predictions about the PW itself. Even for the Crab pulsar, little or no synchrotron emission is seen from the wind in the volume immediately surrounding the pulsar (Schmidt et al. 1979), indicating that the wind itself is not luminous. In general, it is believed that this “cold” PW cannot be observed before its termination in the PWN (Bühler & Blandford 2014). Istomin (2011) argues that the PW could produce detectable synchrotron emission in transient pulsars, and Jones & Odell (1977) show that significant amounts of circular polarization can be produced in homogeneous synchrotron sources. However, as there is no theoretic background to predict the flux densities and the properties of the radio emission of the PW in all pulsars, it is not possible now to test our results on VLA J181335.1–174957. Theoretical studies of radio emission from PW will be highly important for this and future similar works.

Pulsars can also produce radio emission in their off-pulse states, in addition to the pulse emission (Basu et al. 2011). There is evidence that this off-pulse radio emission has a magnetospheric nature and, when present, is typically 10 times weaker than the pulsed radio emission (Basu et al. 2012). A possible interpretation of the steady radio emission detected here is that it corresponds to such off-pulse radio emission, but that in the present case of PSR J1813–1749, the pulse emission itself is not detected because (as mentioned earlier)
The measured spectral index for VLA J181335.1–174957 ($\alpha = -1.3 \pm 0.1$) is consistent with the off-pulse emission to other pulsars ($\alpha_{\text{off-pulse}} = -1.4$; Basu et al. 2012), as is its variability. The off-pulse emission has only been investigated in old long-period pulsars, which is not the case for PSR J1813–1749. The relation of this mechanism with source VLA J181335.1–174957 is still open.

A third possible interpretation of the radio emission detected here is that the pulsar has a young, low-mass stellar companion that is producing gyrosynchrotron emission. The star that produced the pulsar was formed $<$10 million years ago, and it is possible that a low-mass star may be associated with the pulsar. Low-mass stars are frequently magnetically active and may produce significant amounts of gyrosynchrotron emission (e.g., Dzib et al. 2013). This emission is typically strongly variable, on scales of hours to days, with a wide range of spectral indices, usually in the range from $-2$ to $+2$, and they may exhibit significant amounts of circular polarization. There is a precedent for this possibility. In the case of PSR J1603–7202, it has been shown that its low-mass companion produces significant amounts of circularly polarized radio continuum emission (Manchester & Han 2004). However, in this case the large age of the pulsar, $\geq$10 Gyr (Lorimer et al. 1996), implies that the low-mass companion may be a white dwarf. Even though the young low-mass companion hypothesis provides a plausible explanation, there are also some inconsistencies. Radio emission from magnetically active stars is usually strongly variable in flux, in circular polarization, and in spectral index. This is inconsistent with the period of moderate variability of VLA J181335.1–174957 documented here. It should be pointed out, however, that there is a set of young intermediate-mass stars that show circular polarization and no detectable variability (e.g., the sources GBS-VLA J162634.17–242328.4 and GBS-VLA J162749.85–242540.5 in Dzib et al. 2013). On the other hand, the orbit between the pulsar and the putative stellar companion would have to be nearly in the plane of the sky since no periodicities were reported in the X-ray timing observation of Halpern et al. (2012). Furthermore, at distances $\geq$4.8 kpc (Halpern et al. 2012) this would be one of the brightest gyrosynchrotron stars known, comparable only to the brightest similar sources in Orion (Zapata et al. 2004).

Finally, the solution to the enigma may be surprisingly simple. F. Camilo et al. (2018, in preparation) have proposed that PSR J1813–1749 is the most scattered pulsar known and that the pulses become evident only at high frequencies.

5. Conclusions

We presented new deep interferometric VLA observations and single-dish Effelsberg observations of the continuum radio source VLA J181335.1–174957, which has been related to the high-energy pulsar PSR J1813–1749 and to the TeV source HESS J1813–178. The radio continuum source was detected in 10 different epochs with the VLA. The observations showed that VLA J181335.1–174957 is variable, with a circular polarization of $\sim$50% and a spectral index of ($\alpha = -1.3 \pm 0.1$). These parameters indicate that the radio emission has a nonthermal nature. The observations with the Effelsberg telescope, however, find no pulse emission and support the idea suggested by Halpern et al. (2012) that the steady VLA radio source is not the integrated radio pulse emission.

We have discussed three different possibilities of the nature of VLA J181335.1–174957. The most promising explanations of the radio continuum emission are that it corresponds either to the PW or to magnetospheric emission from the pulsar (also known as off-pulse emission). The former explanation is very exciting since it would indicate the first detection of a PW. However, information on PWs and the off-pulse emission is still scarce, so we cannot currently favor or discard either of these possibilities. A third explanation is that PSR J1813–1749 has a low-mass stellar companion that produces the nonthermal radio emission. In this case, VLA J181335.1–174957 is not directly related to the pulsar. However, there is no independent evidence (e.g., based on timing) that PSR J1813–1749 has a companion. The enigma may have a surprisingly simple solution: F. Camilo et al. (2018, in preparation) have found that PSR J1813–1749 is the most scattered pulsar known and that observations made at higher frequencies are consistent with the radio emission being the time-averaged pulsed emission.

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Facilities: VLA, Effelsberg Telescope.

Software: CASA (McMullin et al. 2007), BLOBCAT (Hales et al. 2012), PSRIX (Lazarus et al. 2016), NE2001 (Cordes & Lazio 2002), and YMN16 (Yao et al. 2017).

Appendix

Other Radio Sources

In order to detect the weakest sources in the field we combined the observation of project 17B-028 to produce two deep images (one for each frequency band). The final noise level in both images is $\sim$4 $\mu$Jy. Then, following Medina et al. (2018), we used the BLOBCAT software (Hales et al. 2012) to search for peaks above five times the noise level. To consider a source as real we use the following criteria: (i) the source has a counterpart at any other wavelength, or (ii) its signal-to-noise ratio is above seven.

Under the above criteria, we detected 27 radio sources from which seven are massive stars, and another is related to a submillimeter source. The remaining sources do not have any reported counterparts. Most of the detected radio sources are compact or slightly resolved but two (VLA J181328.00–174958.0 and VLA J181329.58–174829.4) are clearly extended. All detected radio sources and their measured fluxes are listed in Table 2. The spectral index was calculated for compact sources detected in both bands and is also shown in Table 2. Now, we will briefly discuss the most interesting sources.

VLA J181328.00–174958.0 appears as an irregularly shaped source in the X-band image. In the C-band image, on the other hand, a clear shell-like morphology is recovered (see Figure 3, left panel). This source is surrounded by evolved massive stars, so its location and morphology suggest that it may be an SNR. We cannot discard the possibility, however, that it is an H II
region, a planetary nebula, or the nebula around an evolved massive star (i.e., Duncan & White 2002). The smaller flux density at the X band, as compared to the C band, supports an SNR nature, but the modest short spacing coverage of our data could introduce systematic errors in the flux densities of the extended sources. More information is needed to clarify its nature.

VLA J181348.28–174539.2 is associated with the submillimeter source AGAL G012.904–00.031 (Contreras et al. 2013) and with the methanol maser MMB G012.904–00.031 (Green et al. 2010).
Associations between dense submillimeter and methanol masers are usually related to massive star formation (Urquhart et al. 2013), suggesting that VLA J181348.28–174539.2 is related to a massive young stellar object.

VLA J181329.58–174829.4 is a resolved radio source with an arc-like morphology (see Figure 3, right panel). Wind collision regions (WCRs) in massive binary stars may produce radio emission with this kind of structure (e.g., Ortiz-León et al. 2011). Interestingly, the apex of the arc points to another radio source, VLA J181327.85–174843.7. Thus, we suggest that the first source is a WCR and the second source is a massive star. Its massive companion should be closer and at the east side of VLA J181329.58–174829.4.

The massive stars with detected radio counterparts in Table 2 are part of a young massive cluster discovered by Messineo et al. (2008). To our knowledge this is the first detection at radio frequencies of these massive stars.

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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
Aramugasamy, P., Pavlov, G. G., & Kargaltsev, O. 2014, ApJ, 790, 103
Basu, R., Athreya, R., & Mitra, D. 2011, ApJ, 728, 157
Basu, R., Mitra, D., & Athreya, R. 2012, ApJ, 758, 91
Brazier, K. T. S., & Johnston, S. 1999, MNRAS, 305, 671
Brogan, C. L., Gaensler, B. M., Gelfand, J. D., et al. 2005, ApJL, 629, L105
Bühler, R., & Blandford, R. 2014, RPPh, 77, 066901
Camilo, F., Ransom, S. M., Chatterjee, S., Johnston, S., & Demorest, P. 2012, ApJ, 746, 63
Conteras, Y., Schuller, F., Urquhart, J. S., et al. 2013, A&A, 549, A45
Cordes, J. M., & Lazio, T. J. W. 2002, arXiv:astro-ph/0207156
Duncan, R. A., & White, S. M. 2002, MNRAS, 330, 63
Dzib, S., Loinard, L., & Rodríguez, L. F. 2010, RMxAA, 46, 153
Dzib, S. A., Loinard, L., Mioduszewski, A. J., et al. 2013, ApJ, 775, 63
Espinoza, C. M., Lyne, A. G., Stappers, B. W., & Kramer, M. 2011, MNRAS, 414, 1679
Fang, J., & Zhang, L. 2010, ApJ, 718, 467
Funk, S., Hinton, J. A., Morinjuch, Y., et al. 2007, A&A, 470, 249
Gaensler, B. M., & Slane, P. O. 2006, ARA&A, 44, 17
Gotthelf, E. V., & Halpern, J. P. 2009, ApJL, 700, L158
Green, J. A., Caswell, J. L., Fuller, G. A., et al. 2010, MNRAS, 409, 913
Hales, C. A., Murphy, T., Curran, J. R., et al. 2012, MNRAS, 425, 979
Halpern, J. P., Gotthelf, E. V., & Camilo, F. 2012, ApJL, 753, L14
Helfand, D. J., Becker, R. H., White, R. L., Fallon, A., & Tuttle, S. 2006, AJ, 131, 2525
Helfand, D. J., Gotthelf, E. V., Halpern, J. P., et al. 2007, ApJ, 665, 1297
Istomin, Y. N. 2011, Ap&SS, 331, 127
Jones, T. W., & Odell, S. L. 1977, ApJ, 214, 522
Kramer, M., Lyne, A. G., O’Brien, J. T., Jordan, C. A., & Lorimer, D. R. 2006, Sci, 312, 549
Lazarus, P., Karuppasamy, R., Graikou, E., et al. 2016, MNRAS, 458, 868
Lorimer, D. R., Lyne, A. G., Bailes, M., et al. 1996, MNRAS, 283, 1383
Lorimer, D. R., Lyne, A. G., McLaughlin, M. A., et al. 2012, ApJ, 758, 141
Manchester, R. N., & Han, J. L. 2004, ApJ, 609, 354
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
Medina, S.-N. X., Dzib, S. A., Tapia, M., Rodríguez, L. F., & Loinard, L. 2018, A&A, 610, A27
Messineo, M., Figer, D. F., Davies, B., et al. 2008, ApJL, 683, L155
Ortiz-León, G. N., Loinard, L., Rodríguez, L. F., Mioduszewski, A. J., & Dzib, S. A. 2011, ApJ, 737, 30
Ransom, S. M. 2001, PhD thesis, Harvard Univ.
Rees, M. J., & Gunn, J. E. 1974, MNRAS, 167, 1
Reimer, O., Funk, S., Hinton, J. A., et al. 2008, in AIP Conf. Ser. 1085, 4th Int. Meeting on High Energy Gamma-Ray Astronomy, ed. F. A. Aharonian, W. Hofmann, & F. Rieger (Melville, NY: AIP), 376
Schmidt, G. D., Angel, J. R. P., & Beaver, E. A. 1979, ApJ, 227, 106
Ubertini, P., Bassani, L., Malizia, A., et al. 2005, ApJL, 629, L109
Urquhart, J. S., Moore, T. J. T., Schuller, F., et al. 2013, MNRAS, 431, 1752
Watters, K. P., & Romani, R. W. 2011, ApJ, 727, 123
Yao, J. M., Manchester, R. N., & Wang, N. 2017, ApJ, 835, 29
Zapata, L. A., Rodríguez, L. F., Kurtz, S. E., & O’Dell, C. R. 2004, AJ, 127, 2252