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VERY LONG BASELINE INTERFEROMETRY SEARCH FOR THE RADIO COUNTERPART OF HESS J1943+213

K. É. Gabányi[1,5], G. Dubner[2], E. Giacani[2,6], Z. Paragi[3], S. Frey[4], and Y. Pidopryhora[3]
[1] Konkoly Observatory, Research Centre for Astronomy and Earth Sciences of the Hungarian Academy of Sciences,
P.O. Box 67, Budapest H-1525, Hungary; gabanyi@konkoly.hu
[2] Instituto de Astronomía y Física del Espacio (CONICET-UBA), CC 67, Suc. 28, 1428 Buenos Aires, Argentina
[3] Joint Institute for VLBI in Europe, Postbus 2, 7990 AA Dwingeloo, The Netherlands
[4] FÖMI Satellite Geodetic Observatory, P.O. Box 585, H-1592 Budapest, Hungary

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ABSTRACT

HESS J1943+213, a TeV point source close to the Galactic plane recently discovered by the H.E.S.S. Collaboration, was proposed to be an extreme BL Lacertae object, though a pulsar wind nebula (PWN) nature could not be completely discarded. To investigate its nature, we performed high-resolution radio observations with the European Very Long Baseline Interferometry Network (EVN) and reanalyzed archival continuum and H I data. The EVN observations revealed a compact radio counterpart of the TeV source. The low brightness temperature and the resolved nature of the radio source are indications against the beamed BL Lacertae hypothesis. The radio/X-ray source appears immersed in a ∼1′ elliptical feature, suggesting a possible galactic origin (PWN nature) for the HESS source. We found that HESS J1943+213 is located in the interior of a ∼1° diameter H I feature and explored the possibility of them being physically related.

Key words: ISM: supernova remnants – radio continuum: general – radio lines: ISM – techniques: interferometric – X-rays: individuals (CXOU J194356.2+211823)

Online-only material: color figure

1. INTRODUCTION

The High Energy Stereoscopic System (HESS) consists of four imaging atmospheric Cerenkov telescopes situated in the Khomas Highland of Namibia (Aharonian et al. 2006). The HESS Collaboration has been surveying the Galactic plane for new very high energy (VHE) gamma-ray sources (that is, with energies greater than 100 GeV). Recently, HESS Collaboration et al. (2011) reported the discovery of an unresolved VHE gamma-ray source close to the Galactic plane, HESS J1943+213, with an integrated flux above 470 GeV corresponding to ∼2% of the Crab Nebula flux. Between 470 GeV and ∼6 TeV, the spectrum of this source is well described by a power law with photon index $\Gamma = 3.1$. The conducted search for multi-wavelength counterparts revealed the presence of a hard X-ray source, observed by *INTEGRAL*, IGR J19443+2117, in the vicinity of the HESS source. Landi et al. (2009) analyzed the data of the X-ray telescope on board the *Swift* satellite to search for soft X-ray counterparts of three *INTEGRAL* sources, among them IGR J19443+2117; they found a firm localization of this source in soft X-rays (SWIFT J1943.5+2120). Later, Tomsick et al. (2009) conducted *Chandra* X-ray observations of several *INTEGRAL* sources, including IGR J19443+2117, to localize and measure their soft X-ray spectra. They concluded that IGR J19443+2117 is associated with the *Chandra* source CXOU J194356.2+211823 and the probability of spurious association is only 0.39%. According to the precise *Chandra* measurement, the X-ray source is located 23″ away from HESS J1943+213 but still within the HESS error circle, leading HESS Collaboration et al. (2011) to identify the X-ray source with the HESS source. All the proposed counterparts of HESS J1943+213 discussed by HESS Collaboration et al. (2011) are located within the 68% best-fitting source position confidence level contour of HESS J1943+213 (see Figure 6 in HESS Collaboration et al. 2011).

In a search for a radio counterpart, a possible source is found in the U.S. National Radio Astronomy Observatory (NRAO) Very Large Array (VLA) Sky Survey (NVSS). The source, NVSS J194356+211826 (Condon et al. 1998), is located 24.″7 away from the HESS position (still within the HESS error circle) and 3.″5 away from the *Chandra* position. The *Chandra* source is outside the NVSS error circle.

HESS Collaboration et al. (2011) discuss possible origins for HESS J1943+213, proposing that it can be either a gamma-ray binary, a pulsar wind nebula (PWN), or an active galactic nucleus (AGN). The binary hypothesis is discarded because all known gamma-ray binaries contain a massive bright stellar companion visible in the infrared/optical band, and no evidence of such star is seen in the data, implying a minimum distance of 25 kpc, thus beyond the outer edge of the Galaxy. The PWN hypothesis would be plausible, since the strong magnetic fields cause rapid energy loss of accelerated particles, preventing high-energy particles from moving far from the source, like in the case of the Crab Nebula, making this kind of source appear point-like on the scale of the HESS angular resolution. In fact, 34 PWNe have been detected up to date in the TeV range,[7] all of them point-like in appearance, constituting the most abundant class of VHE sources detected by Cerenkov telescopes. In the case of HESS J1943+213, HESS Collaboration et al. (2011) conclude that the small gamma-ray to X-ray flux ratio implies that, if this is the origin of the VHE emission, the nebula must be very young, approximately 1000 years old, and located at a distance of ⩽16 kpc. However, the VHE spectrum of HESS J1943+213 is significantly softer than the spectra of all known VHE PWNe, a fact that, when considered together with the lack of extended

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[5] Also at FÖMI Satellite Geodetic Observatory, P.O. Box 585, H-1592 Budapest, Hungary.

[6] Also at FADU, Universidad de Buenos Aires, Argentina.

[7] http://tevcat.uchicago.edu/. TeVCat is maintained by S. Wakely and D. Horan and is partially supported by the NSF.

X-ray emission in the *Chandra* images, weakens the hypothesis of the VHE source being a PWN. Finally, HESS Collaboration et al. (2011) discuss the possibility of HESS J1943+213 being a blazar. Blazars are AGNs where a relativistic jet pointing close to the line of sight produces Doppler-boosted emission (Urry & Padovani 1995). According to HESS Collaboration et al. (2011), HESS J1943+213 would be classified as a radio-loud, X-ray-strong BL Lac object belonging to the high-frequency-peaked BL Lac (HBL) class. The drawback of this hypothesis is the lack of a high-energy counterpart (in the 100 MeV–100 GeV domain), a characteristic that is unusual for these objects. Also the clearest characteristic of blazars, their variability on all timescales, was not detected in the case of HESS J1943+213.

After weighting the different pros and cons, HESS Collaboration et al. (2011) conclude that the identification of HESS J1943+213 as an extreme HBL object is the most plausible origin.

Since the PWN nature cannot be completely rejected, it is very important to identify as accurately as possible the counterparts of HESS J1943+213 in other spectral ranges with the purpose of understanding the true nature of the VHE emission. With this objective in mind, we conducted exploratory very long baseline interferometry (VLBI) continuum observation of NVSS J194356+211826 (hereafter J1943+2218) with the European VLBI Network (EVN) at 1.6 GHz frequency. This observation allowed us to spatially resolve the radio source and to obtain its positional information with the precision of a few milliarcseconds (mas). We complemented the high angular resolution study with the analysis of archival 1.4 GHz VLA radio continuum data at intermediate angular resolution and investigated the Galactic interstellar gas in an extended field around the VHE source. We describe the observations and data reduction in Section 2 and present our results in Section 3. In Section 4, we discuss our findings, in light of possible scenarios: the source being HBL (Section 4.1), a gamma-ray binary (Section 4.2), or a PWN (Section 4.3). We summarize our work in Section 5.

2. OBSERVATIONS AND DATA REDUCTION

The exploratory EVN observation of J1943+2118 took place on 2011 May 18 (project id: RSG03). At a recording rate of up to 1024 Mbit s^{-1}, seven antennas participated in this e-VLBI experiment: Effelsberg (Germany), Jodrell Bank Lovell Telescope (UK), Medicina (Italy), Onsala (Sweden), Toruń (Poland), Hartebeesthoek (South Africa), and the phased array of the Westerbork Synthesis Radio Telescope (WSRT, The Netherlands). In an e-VLBI experiment (Szomoru 2008), the signals received at the remote radio telescopes are streamed over optical fiber networks directly to the central data processor for real-time correlation. The correlation took place at the EVN data processor in the Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands, with 2 s integration time. The observations lasted for 2 hr. Eight intermediate-frequency channels were used in both right and left circular polarizations. The total bandwidth was 128 MHz per polarization.

The target source was observed in phase-reference mode to obtain precise relative positional information. It was crucial for strengthening the identification of the source, since there was a significant difference between the NVSS peak position and the *Chandra* position. The phase-reference calibrator source J1946+2300 is separated from the NVSS radio source by $1\overset{\circ}{.}77$ in the sky. Its coordinates in the current second realization of the International Celestial Reference Frame are right ascension $\alpha_0 = 19^{\mathrm{h}}46^{\mathrm{m}}6\overset{\mathrm{s}}{.}25140484$ and declination $\delta_0 = +23^\circ0'4\overset{''}{.}4144890$ (Fey et al. 2009). The target–reference cycles of ∼5 minutes allowed us to spend ∼3.5 minutes on the target source in each cycle, thus providing almost 1.3 hr total integration time on J1943+2118. The source position turned out to be offset from the phase center position (taken from the NVSS catalog) by ∼4″, but still within the undistorted field of view of the EVN.

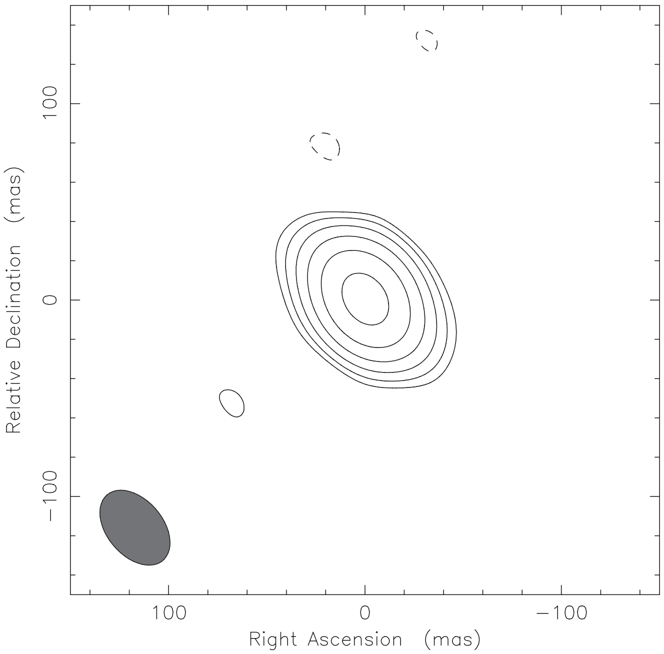

Figure 1. 1.6 GHz EVN image of J1943+2118. The lowest contours are drawn at ±0.6 mJy beam^{-1}. The positive contour levels increase by a factor of two. The peak brightness is 25.3 mJy beam^{-1}. The Gaussian restoring beam shown in the lower left corner is 43.9 mas × 28.5 mas (FWHM) with major-axis position angle $40\overset{\circ}{.}3$.

The NRAO Astronomical Image Processing System (AIPS; e.g., Diamond 1995) was used for the data calibration in the standard way. We refer to Frey et al. (2008) for the details of the data reduction and imaging. The calibrated data were exported to the Caltech Difmap package (Shepherd 1997) for imaging. Phase self-calibration was only performed at the most sensitive antennas (Effelsberg, Jodrell Bank, WSRT). No amplitude self-calibration was applied. Finally, the longest baselines (from European telescopes to Hartebeesthoek) were excluded from the imaging because the signal was barely above the noise level due to the resolved nature of the source. The resulting image of J1943+2118 is displayed in Figure 1.

We also analyzed archival VLA continuum data (project AH196, observing date 1985 September 30). These observations were taken from the region around our target source at 1.4 GHz, in the C configuration of the array, thus improving the angular resolution by a factor of three compared to the NVSS survey, which was performed with the most compact D configuration of the VLA.

The archival experiment AH196 included five different pointings covering a region of about $2\overset{\circ}{.}4 \times 1^\circ$ around our source of interest. The calibration was performed in AIPS, using 3C 48 as the primary flux density calibrator. We used Difmap to obtain the image shown in Figure 2.

We also investigated the neutral hydrogen (H i) radio emission in a large field around the VHE source. To carry out this study, we made use of the data from the VLA Galactic Plane Survey (VGPS; Stil et al. 2006).

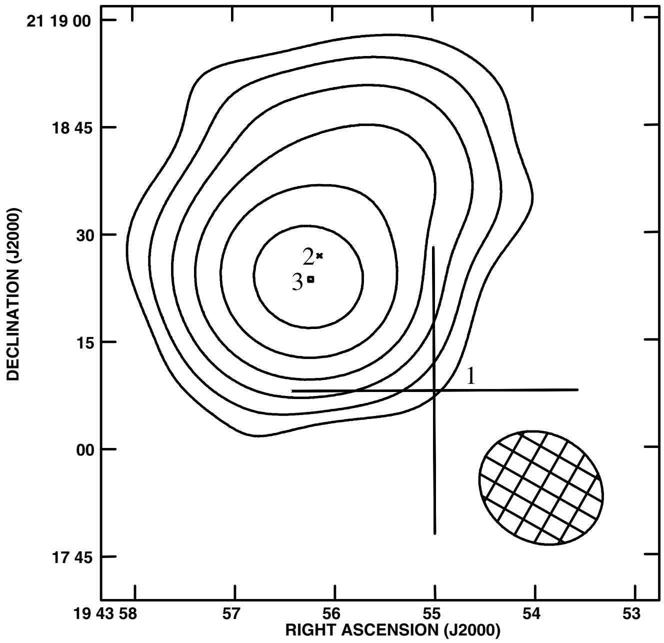

Figure 2. 1.4 GHz VLA C-configuration image of J1943+2118. The peak brightness is 60 mJy beam^{-1}. The lowest contours are drawn at ±1.2 mJy beam^{-1}, and the positive contour levels increase by a factor of two. The Gaussian restoring beam shown in the lower right corner is $17''.8 \times 15''.1$ with major-axis position angle $60^{\circ}.1$. Label number 1 indicates the TeV source position and its 90% error measured by HESS The NVSS source position and the position of the X-ray counterpart are labeled as number 2 and number 3, respectively. The sizes of the symbols represent the errors of the corresponding position measurements. The *Chandra* position coincides with the position of the radio source derived from our phase-referenced EVN observation. (The accuracy of the EVN position is superior to that of the X-ray; therefore, it cannot be distinctively displayed in this figure.)

3. RESULTS

3.1. *Radio Continuum*

3.1.1. *EVN Results*

The phase-referenced exploratory EVN observation provided accurate equatorial coordinates for J1943+2118: $\alpha = 19^{h}43^{m}56^{s}.2372 \pm 0^{s}.0001$ and $\delta = 21^{\circ}18'23''.402 \pm 0''.002$. This position agrees well, within the *Chandra* uncertainties, with the coordinates of CXOU J194356.2+211823, the X-ray source proposed to be the counterpart of the HESS point source (HESS Collaboration et al. 2011). Therefore, we confirm that they are the same object that is very likely associated with the VHE emission detected by HESS. It has to be noted that the difference between the new, accurate position measurement and the position given in the NVSS catalog is $3''.75$.

We used the Difmap package to fit a circular Gaussian brightness distribution model component to the VLBI visibility data. The feature in our EVN image can be well described with a component of 31 mJy flux density and 15.8 mas angular size (FWHM). Since J1943+2118 is very close to the Galactic plane (at about $-1^{\circ}.3$ Galactic latitude), angular broadening caused by the intervening ionized interstellar matter can distort the image of a distant compact radio source. It is important to disentangle whether the observed size of the source is intrinsic or it is an observational effect. According to the model of Cordes & Lazio (2002), the maximal amount of angular broadening of a point source in this direction at 1.6 GHz (the frequency of our EVN observation) is expected to be 3.34 mas. Therefore, even if we take this effect into account, the "de-broadened" source size remains quite large.

The flux density recovered in our high-resolution EVN observation is only one-third of the value reported by NVSS at 1.4 GHz, 102.6 ± 3.6 mJy. To investigate the discrepancy between the flux density values, we analyzed the WSRT synthesis array data taken during our EVN experiment. The obtained flux density value, ∼95 mJy, still agrees well with the value reported in the NVSS for J1943+2118. Thus, we can conclude that J1943+2118 is likely to be extended and the high-resolution EVN observation resolved out a significant portion of its large-scale structure. This conjecture is confirmed with the archival VLA C-array data (Section 3.1.2 and Figure 2). According to those, the flux density of the source is 91 ± 5 mJy, which agrees with the flux density values derived from the two other (the NVSS and the WSRT-only) lower-resolution data sets.

3.1.2. *VLA C-array Results*

The $\sim 16''$ FWHM resolution image obtained from the VLA C-array archival observations revealed an elongated structure with a size of $1'.1 \times 0'.8$ (Figure 2). This shape can naturally explain why the NVSS cataloged position, obtained from lower-resolution observations, is $\sim 4''$ off the position of the EVN point source. In Figure 2, label 1 indicates the TeV source position (and the 90% error box), label 2 indicates the NVSS tabulated position, and label 3 indicates the coinciding *Chandra* X-ray and EVN radio positions. The shift between points 2 and 3 is exactly in the direction of the source extension.

3.1.3. *Radio-continuum Emission at Large Scale*

Finally, to gain insight into the field where HESS J1943+213 is located, and to search for possibly associated extended emission around the gamma-ray source, we inspected the VGPS image of the radio continuum emission at 1.4 GHz in a $5^{\circ} \times 5^{\circ}$ area around the source position. The field appears almost empty around J1943+2118 with no trace of diffuse emission at the sensitivity of this survey.

3.2. *H* I *Emission around the Position of HESS J1943+213*

We also analyzed the H I emission in a large $5^{\circ} \times 5^{\circ}$ field around the source, across the whole observed velocity range between -114 km s^{-1} and +166 km s^{-1}, using data extracted from the VGPS (Stil et al. 2006). We found that in all channel maps between radial velocity $v \approx +50$ km s^{-1} and $v \approx +57$ km s^{-1}, there is a striking, almost complete shell-like feature surrounding the location of J1943+2118 (Figure 3). This H I feature appears at a "forbidden" velocity for the expected rotational properties of the Galactic gaseous disk, since in this direction of the Galaxy the maximum positive velocity (corresponding to the tangent point) is predicted to be about +35 km s^{-1}. We also note that in this direction of the Galaxy, approximately in the middle of the first quadrant, the Galactic disk warps toward positive latitudes (Voskes & Burton 2006), and therefore it is very likely that a feature like this shell, located at a forbidden velocity and at a negative galactic latitude, is unrelated with the normal Galactic gas.

A long time ago Katgert (1969), working on a kinematical analysis of a large number of H I profiles around $l = 60^{\circ}, b = 0^{\circ}$, reported the discovery of a large ring-like object remarkable because its radial velocity (between approximately +46 and +50 km s^{-1}) exceeded the maximum rotation curve velocity. Katgert (1969) suggested that the object would be the remnant

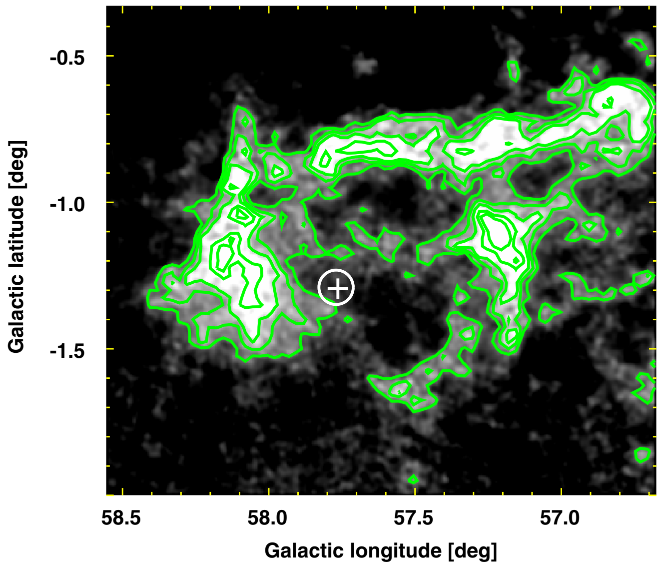

Figure 3. Detailed view of the H I feature surrounding the location of HESS 1J943+213. The cross shows the location of J1943+2118, and the circle is the $2\overset{\prime}{.}8$ confidence size of HESS J1943+213.

(A color version of this figure is available in the online journal.)

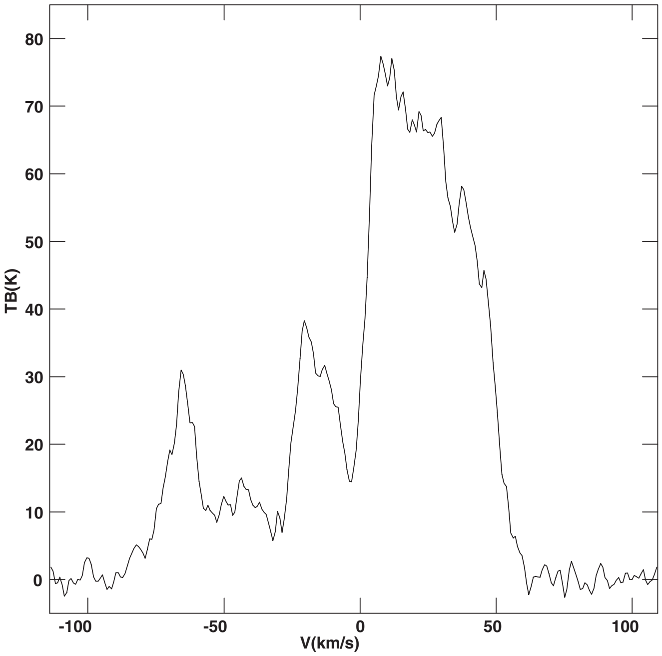

Figure 4. H I spectrum toward J1943+2118. The line of sight along $l = 57\overset{\circ}{.}7$ in the direction of this source crosses the spiral arms Perseus, Scutum, and Sagittarius between the LSR velocities 0 and +60 km s^{-1}, in the interior of the solar circle, and again the Cygnus arm around −20 km s^{-1} and the Scutum-Crux arm near −65 km s^{-1}, corresponding to distances of about 10–11 and 15–16 kpc, respectively, in the outer Galaxy.

of a large-scale explosive event that took place near the Galactic plane that at present had been almost completely decelerated. The H I feature that we identified around HESS J1943+213 lies in the periphery of that object, and it may or may not be part of the same event (in fact Katgert (1969) kinematically identifies the same feature but assumes that it is unrelated because its systemic velocity is larger than +48 km s^{-1}, a rather arbitrary limit chosen to separate components). In any case, this precursory study called attention toward the possible existence of explosive and/or expansive events that took place in this region of the Galaxy in the past. Several of such large H I shells have been detected in our Galaxy (e.g., McClure-Griffiths et al. 2002), and their origin is usually associated with the combined action of stellar winds and subsequent supernova (SN) explosions inside the previously evacuated cavity. It has been proposed that the expansion of such shells can lead to the sequential formation of new stars (e.g., Whitworth et al. 1994; Arnal & Corti 2007), and the most massive of them can end their lives exploding as SNe. As the radio emission associated with HESS J1943+213 is not strictly point-like but, on the contrary, there is evidence that it is spatially extended (with an angular size of about 1′ according to the VLA data), we explored the hypothesis that the gamma-ray emission originates in a PWN formed after the explosion of one of the second-generation stars. H I shells are usually the last vestiges of explosions whose other manifestations already vanished.

The detected H I shell is centered at $\alpha = 19^{\mathrm{h}}43^{\mathrm{m}}23^{\mathrm{s}}, \delta = +21^\circ10'45''$ $(l = 57\overset{\circ}{.}6, b = -1\overset{\circ}{.}25)$, has an angular diameter ∼1°, and can be clearly seen between + 50 and +57 km s^{-1}. Its anomalous velocities preclude the application of Galactic circular rotation models to independently estimate its distance, but if we assume that the detected H I shell is physically associated with HESS J1943+213, it has to be at the same distance.

Very recently on the basis of an H I absorption spectrum toward J1943+2118, Leahy & Tian (2012) proposed that it is located beyond 16 kpc from the Sun. They considered this as evidence of HESS J1943+213 being an extragalactic source. We note that according to the recent velocimetry and cartography of the Milky Way presented by Vallée (2008), in this direction of the Galaxy (Galactic coordinates of HESS J1943+213: $l = 57\overset{\circ}{.}7$, $b = -1\overset{\circ}{.}29$), the farthest Galactic arm reaches distances greater than 20 kpc. Following the best up-to-date velocimetric models (Vallée 2008), the line of sight along $l = 57^\circ$ traverses five spiral arms: Sagittarius, Scutum, and Perseus within the solar circle, and Cygnus, Scutum-Crux, and again Sagittarius in the outer Galaxy, up to at least 22 kpc from the Sun. Figure 4 displays an H I profile traced toward the point radio source. Here it is possible to trace the presence of H I gas above 3σ noise level at least up to $\mathrm{v_{LSR}} \sim -82$ km s^{-1}, corresponding to a distance of ∼18 kpc according to the standard Galactic circular rotation model (Fich et al. 1989). Such a distance is consistent with the column density obtained from dust maps, and the N_{H} obtained from *Chandra* and *Swift* X-ray spectra, as presented by HESS Collaboration et al. (2011). If we assume as a working hypothesis that the observed H I shell is related to the detected radio source and hence to HESS J1943+213, an approximate distance of 17 kpc can be adopted for the H I feature.

At this distance the linear diameter of the H I shell is 300 pc, the H I mass (calculated by integrating all contributions within the shell across all the channels where the shell is present) amounts to $1.4 \times 10^5 (d/17\,\mathrm{kpc})^2\, M_\odot$, and the ambient density is $\sim 0.5 (d/17\,\mathrm{kpc})^{-1}\,\mathrm{cm}^{-3}$.

In this scenario, HESS J1943+2118 would be a PWN left after an SN explosion of which no radio continuum remnant is observed because the shock front expanded into a medium with very low ambient density. The weak point of this picture is that an expansion velocity along the line of sight of about 130 km s^{-1} is required in order to reconcile the observed central velocity of the shell (∼+54 km s^{-1}) with the systemic velocity of HESS J1943+2118 (∼−77 km s^{-1} if it is located at ∼17 kpc). As the shell diameter does not change significantly in size with velocity within the velocity range where it is detected, and it is not possible to clearly identify other portions of the shell in different velocity ranges because of confusion with Galactic emission, we do not have arguments to prove that the shell expands at such velocity.

4. DISCUSSION

4.1. The Blazar Hypothesis

The lack of optical/infrared spectroscopic measurements makes it difficult to unambiguously identify J1943+2118 as a blazar, although HESS Collaboration et al. (2011) mention a preliminary infrared spectrum that shows no obvious emission lines. Based on its spectral energy distribution (SED), the source could belong to the HBL class that makes up the majority of VHE detected AGNs (HESS Collaboration et al. 2011). According to Massaro et al. (2011), the infrared magnitudes measured by the *Wide-field Infrared Survey Explorer* (*WISE*) satellite can be used to distinguish blazars from other extragalactic radio sources. We checked the now available *WISE* All-Sky Data Release (Wright et al. 2010). Based on the *WISE* infrared magnitudes of the Two Micron All Sky Survey source associated with J1943+2118, the source lies within the so-called *WISE* blazar strip, grouped together with confirmed HBL sources.

If we assume that the TeV source is an HBL at a moderate redshift of $z = 0.3$ (most of the HBLs with known redshifts detected in the TeV regime have a redshift $\leqslant 0.3$ according to the currently available data of TeVCat), the observed parameters of the detected point-like source (flux density of 31 mJy, angular size of 15.8 mas) imply a very low brightness temperature of only $T_{\rm B} = 7.7 \times 10^7$ K. Even taking into account a correction for angular broadening of the point source produced by the intervening ionized gas (as discussed in Section 3.1.1), the brightness temperature is still substantially lower than the intrinsic equipartition value estimated for relativistic compact jets ($\sim 5 \times 10^{10}$ K; Readhead 1994). In the case of HBLs, the gamma-ray emission that is Doppler-boosted in the jet is produced by inverse-Compton scattering of ambient low-energy photons. The fundamental parameters of the parsec-scale jets can be inferred from high-resolution VLBI observations. Even considering that the jet bulk Lorentz factors determined from radio data of TeV HBLs are modest ($\Gamma \sim 3$–4; Piner et al. 2010, and references therein), and there are indications for larger jet inclinations with respect to the line of sight ($\sim 15^\circ$–30°; Wu et al. 2007), the measured brightness temperature of J1943+2118 still seems too low. Our value of $T_{\rm B} < 10^8$ K is well below the typical brightness temperatures found for other extensively studied TeV HBLs (10^9–10^{10} K, e.g., Giroletti et al. 2006; Piner et al. 2008, 2010).

There are two possible ways to have higher rest-frame brightness temperature. One is if the source is more distant, located at a higher redshift. However, even assuming an extremely large redshift of $z \approx 6$ (where the most distant known radio-loud quasars are located; Frey et al. 2011), the brightness temperature would only be $\sim 4 \times 10^8$ K. Another possibility to obtain a higher brightness temperature value is, as mentioned before, by assuming that the intrinsic source size is smaller than the observed, because it is broadened by interstellar scattering effects in the ionized turbulent medium of the Milky Way.

If we assume that all the flux density recovered by the EVN measurement (31 mJy) originates from the compact core of the HBL, then its intrinsic size at 1.6 GHz cannot be larger than 1.2 mas in order to measure a brightness temperature of at least 10^{10} K. Consequently, the scattering size at 1.6 GHz must be at least 15.7 mas. Such a value is not unprecedented. For example, Fey et al. (1989) studied several extragalactic lines of sight passing through the Cygnus region of the Milky Way. The largest scattering size measured (at 1.6 GHz) was 28.2 mas for the quasar B2005+403. Two of the most scatter-broadened extragalactic sources have much larger scattering disk sizes: 298 mas and $\sim$4000 mas for B1849+005 (Lazio 2004) and NGC 6334B (Moran et al. 1990), respectively. However, the interstellar "clumps" responsible for these values are identified in all these cases and consequently included in the NE2001 model of Cordes & Lazio (2002). In the case of J1943+2118, no such clump is known (at least yet). Lazio et al. (2008) studied a sample of AGNs and found that the average scattering disk size is 2 mas (at 1 GHz); the largest measured value was 7.8 mas (unfortunately, no AGN was chosen from the longitude region $-60^\circ \leqslant l \leqslant 60^\circ$, where J1943+2118 is located). Fey (1989) examined angular broadening of radio sources near the Galactic plane in the longitude range $20^\circ < l < 90^\circ$ and reported that the observed scattering decreases rapidly with increasing Galactic longitude, reaching a minimum at $l \approx 60^\circ$. Therefore, we do not expect enhanced scattering in the direction of J1943+2118.

Our results also showed that the EVN data recover only one-third of the total flux density of J1943+2118. This is unlike what is usually observed for VLBI-imaged TeV HBLs, where the total radio emission is dominated by the compact mas-scale core. For example, the largest difference between the total (NVSS) and the core (VLBI) flux density is less than 50% in the sample of Giroletti et al. (2006). This and the measured low brightness temperature are indications against the beamed blazar hypothesis.

4.2. The Galactic Gamma-Ray Binary Hypothesis

Although HESS Collaboration et al. (2011) excluded the possibility that HESS J1943+213 is related to a gamma-ray binary, because no bright, early-type star was detected in the system, we discuss whether the observed radio properties fit this scenario.

There are three objects reported in the literature that are considered as classical gamma-ray binaries, PSR B1259-63, LS 5039, and LSI +61 303. In these systems, the binarity is well established. They show GeV and/or TeV emission, with a peak in the SED at MeV–GeV energies. Recently, a fourth system was discovered, HESS J0632+057 (Moldón et al. 2011, and references therein). In all of these systems, the emission is variable and periodic in all wavebands, in contrast with our target HESS J1943+213. All of the sources mentioned above were detected with the VLBI technique on mas scales, with extended and variable structure. The observed brightness temperature due to the resolved structure on mas scales in HESS J1943+213 would be consistent with this scenario. With monitoring observations on VLBI scales at somewhat higher resolution than in our presented exploratory EVN data, one could probe the variable appearance of the source on mas scales. (Moreover, a Galactic source is expected to show a proper motion detectable with VLBI in the future.)

The multi-wavelength properties of gamma-ray binaries have been interpreted with either microquasar jets (e.g., Bosch-Ramon & Khangulyan 2009) or particle acceleration in shocks between a relativistic pulsar wind and the wind from the companion star (e.g., Tavani & Arons 1997; Dubus 2006). Most notably, in the case of LSI +61 303, Dhawan et al. (2006) showed that the microquasar interpretation of the system does not agree with the variable structure observed with the Very Long Baseline Array, showing orbital modulation of the extended structure as expected in the shocked-wind scenario.

What is, however, not observed in gamma-ray binaries is the prominent, arcminute-scale radio structure present in HESS J1943+213. It is hard to reconcile with either the microquasar jet or the colliding wind scenario. Therefore, in addition to the missing optical counterpart and the lack of (periodic) variability, we find another piece of evidence against the gamma-ray binary interpretation of HESS J1943+213.

4.3. Other Galactic Origin

In the following, we investigate the hypothesis whether HESS J1943+213 (and consequently its radio counterpart, J1943+2118) can be a Galactic object, specifically a PWN.

If the paradigmatic PWNe Crab and 3C 58 were located at a distance of 17 kpc, as the proposed distance for J1943+2118, their angular size in radio wavelengths would be of the order of $\sim 0\farcm8$ for Crab and $\sim 1\farcm7$ for 3C 58. This is in excellent agreement with the size of the structure around J1943+2118 as seen from the VLA-C observations (Figure 2). The size of the PWN in X-rays is generally smaller than in radio due to the smaller synchrotron lifetimes of the higher-energy electrons (Slane et al. 2000), thus explaining why *Chandra* detected it as a point-like source. Besides, the radio spectral index −0.32 reported by Vollmer et al. (2010) for the NVSS point source coincident with J1943+2118 is compatible with the standard spectral indices of PWNe (between 0 and −0.3; Gaensler & Slane 2006). In that sense, the new radio results do not contradict a PWN hypothesis.

Even when we cannot unambiguously prove that the H I shell and HESS J943+213 are associated, it is worthwhile to explore the idea of having gamma-ray emission related to peculiar features in the Galactic gas. Renaud et al. (2008) showed that the "dark" VHE source HESS J1503−582, which lacks any traditional counterpart, is spatially coincident with the Forbidden Velocity Wing FVW 319.8+0.3 and proposed that the objects can be associated. Kang & Koo (2007) reported on the existence of 81 FVWs. The FVWs are faint, wing-like H I features at velocities beyond the boundaries allowed by Galactic rotation. Later Kang, Koo, & Salter (2010) explored some of them at higher resolution using the Arecibo and Green Bank radio telescopes, concluding that a significant fraction of the FVWs are expanding shells with physical parameters consistent with those expected from very old supernova remnants (SNRs).

In this context it is interesting to investigate how often a TeV source can be found associated with a large H I shell and/or FVW structures. As a first approximation we confronted lists of high-energy sources with the results of McClure-Griffiths et al. (2002, and references therein) in their search for large H I shells in a field of over 2000 deg^2 in the third and fourth Galactic quadrants (region $253° \leqslant l \leqslant 358°$, $-10° \leqslant b \leqslant +10°$). We found the following: the studied region contains 19 Galactic H I shells and 31 TeV gamma-ray sources. Among the 31 TeV sources, 11 were identified with galactic objects (shell SNRs, massive stars clusters, and X-ray binaries), 11 as PWNe, and 9 still remain unidentified. The cross-checking between H I features and TeV sources indicates that among the 11 identified with galactic objects, only 1 coincides with an H I shell; from the 11 classified as PWNe, 2 appear related to H I shells; and, notably, 7 out of the 9 unidentified TeV sources lie clearly within or on the borders of H I shells (G. Dubner et al. 2012, in preparation). The sizes and ambient densities of these shells are comparable to those of our discovery.

Though the study is in progress and the statistic is incomplete, these numbers are suggestive that the positional agreement shown by Renaud et al. (2008) may be a quite common phenomenon. That is, VHE point-like or extended sources that could not be identified with known Galactic or extragalactic objects might be related with large H I shells, the fossil remains of the combined action of powerful stellar winds and SN explosions.

5. SUMMARY

The exploratory EVN observation allowed us to pinpoint with high precision a radio source spatially coincident with the *Chandra* X-ray source proposed to be the counterpart of the TeV source HESS J1943+213. It confirms that all the reported multi-wavelength sources are physically related to the same object. The EVN observation also revealed that the radio source is highly resolved, and its brightness temperature is significantly lower than the intrinsic equipartition value estimated for relativistic compact jets (Readhead 1994). Additionally, from the study of the radio continuum emission at intermediate angular resolution based on archival VLA C-array observations, we could identify the presence of an elongated feature, about 1′ in size, around the point source. These results from radio continuum observations pose difficulties to the TeV source identification as an HBL. To be able to reconcile the large source size with the object being an HBL, we have to introduce angular scattering by a currently unknown intervening galactic "clump" of ionized matter that should be similar in the scattering characteristics to the ionized material in the Cygnus superbubble region, however much smaller in size. This hypothesis could be investigated via future multi-frequency VLBI observations, since we expect that at low frequencies (below at least ∼10 GHz), the apparent source size would change according to the scattering law, roughly with the square of the observing frequency.

We also discussed the possibility of HESS J1943+213 being a gamma-ray binary. While part of the characteristics detected by our EVN observation can be explained within a gamma-ray binary scenario, none of the known gamma-ray binaries exhibit large arcminute-scale structure, similar to the one revealed by the archival VLA data in HESS J1943+213. This finding, together with the missing early-type companion star and the lack of periodic variability, is an indication against the gamma-ray binary hypothesis.

Additionally, we studied the large-scale H I emission in an extended field around the TeV source. The H I spectral line data revealed a shell-like feature around HESS J1943+213. In spite that we do not yet have unequivocal evidence confirming that the two objects are associated, a scenario where the TeV emission detected by HESS is produced by a distant PWN would be compatible with some imprints left in the interstellar medium by the past events that ended in an SN explosion in the region. This object would be placed in the outermost parts of the Galaxy, beyond 16 kpc according to Leahy & Tian (2012), but still within the external arms of the Milky Way.

Higher-resolution VLA observations already initiated by our group would be able to shed light on the structure of the arcminute-scale radio feature and its relation to the compact object detected by our EVN observation. In the PWN scenario, if we assume that the compact bright feature detected by EVN is solely emitted by the pulsar itself, then according to, e.g., Hankins et al. (1993), the observed flux density must be beamed and intrinsically periodic. The scattering along the line of sight to HESS J1943+213, when put at 17 kpc distance, would not smear out the pulses (Cordes & Lazio 2002). Thus, searching for pulsed radio emission would help to reveal the nature of the object, but this tool is useful only if the pulsar responsible for blowing the PWN is beamed toward us.

Finally, from a quick inspection of the distribution of the large H I shells and FVW structures that are being discovered in our Galaxy and the distribution of the unidentified HESS sources, we find that a significant fraction (seven out of nine in the third and fourth Galactic quadrants) are positionally coincident. This result is part of a larger study underway and at present is only a suggestive conclusion.

To summarize, based on the currently available observational facts, the true nature of the TeV source HESS J1943+213 still cannot be decided unambiguously. However, if we conclude that it is an HBL object, then either it is not beamed, in contrast with what we currently know about HBLs, or a significant amount of highly turbulent ionized material is needed in the line of sight toward this source to explain its apparent size. On the other hand, if the source is indeed a PWN and is related to the discovered H I feature, then the importance of the reported discovery resides not only in the fact that it naturally explains the origin of the TeV emission, but also, as remarked by Koo et al. (2006), in that it helps to solve the long-standing problem of the "missing" Galactic SNRs, where the detected SNRs barely make up 1% of the expected number. It also opens a new path to investigate the nature of the dark TeV sources.

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