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A pulsar wind nebula associated with PSR J2032+4127 as the powering source of TeV J2032+4130

Javier Moldón*,
ASTRON, the Netherlands Institute for Radio Astronomy, and Departament d'Astronomia i Meteorologia, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB
E-mail: moldon@astron.nl

Josep M. Paredes, Marc Ribó, V. Bosch-Ramon
Departament d'Astronomia i Meteorologia, Institut de Ciències del Cosmos, Universitat de Barcelona, IEEC-UB

V. Zabalza
Department of Physics and Astronomy, The University of Leicester

J. Martí
Departamento de Física, Escuela Politécnica Superior, Universidad de Jaén

M. Kramer
Max-Planck-Institut für Radioastronomie, and Jodrell Bank Centre for Astrophysics, The University of Manchester,

A. G. Lyne, B. W. Stappers
Jodrell Bank Centre for Astrophysics, The University of Manchester,

The very-high-energy gamma-ray source TeV J2032+4130, in the Cygnus region, was the first source discovered of a population of extended TeV sources without low-frequency counterparts. In its field there is a pulsar, namely PSR J2032+4127, which has been detected by *Fermi* in gamma-rays and in radio by the Green Bank Telescope (GBT). We report on an ongoing multi-wavelength campaign to search for a pulsar wind nebula associated with PSR J2032+4127 through radio and X-ray observations. Moreover, we are conducting a multi-epoch very long baseline interferometr (VLBI) campaign with the European VLBI network (EVN) in order to measure the pulsar proper motion and to find its relation with the radio nebula and the TeV extended source. All these results together, combined with a theoretical modeling of the system, enable us to propose a conceivable physical scenario in which the extended radio, X-ray and TeV emissions are accounted for.

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*Speaker.

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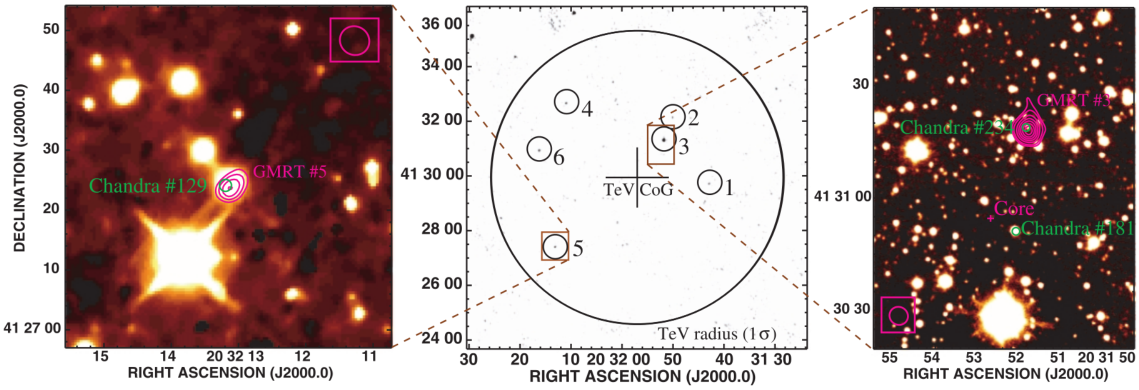

Figure 1: The central panel shows a deep GMRT map of the TeV J2032+4130 field at the 49 cm wavelength (610 MHz). The CoG of HEGRA TeV emission and its statistical error are indicated by the central cross, while the central circle illustrates the 1σ radius of its extended angular size. This GMRT map has a synthesized beam of $5.0'' \times 4.8''$ and position angle of 33°. The grey scale is linear and goes from 0 to 2.15 mJy beam^{-1}. **Left.** Zoomed view of GMRT source#5 coincident with a bright optical/near infrared early type star according to CAHA *Ks*-band observations. This object also has a *Chandra* X-ray counterpart indicated by the small red circle. **Right.** The same area containing the bright GMRT source #3. Figure from [6]

1. Introduction

The new generation of Cherenkov telescopes has revealed a population of ~ 90 Galactic TeV sources (see [1]). About 1/3 of them are extended TeV sources associated with Pulsar Wind Nebulae (PWNe) although 52% of the population still remains unidentified or with no firm low-energy counterpart, the so-called dark accelerators. The first discovered of these sources, and still unidentified, is TeV J2032+4130, discovered by HEGRA [2, 3], and later confirmed by MAGIC [4] and VERITAS [5]. The source has a size of $5''$ and exhibits a steady flux with a hard spectrum. The extended and steady nature, together with its location close to the Galactic plane in the Cygnus OB2 region, clearly suggest a Galactic nature for this source.

The authors in [6, 7] conducted a detailed multi-wavelength study of TeV J2032+4130. In particular, they performed radio interferometric observations with the Giant Metrewave Radio Telescope (GMRT) at 610 MHz, with the Very Large Array (VLA) in C configuration at 1.4 and 5 GHz, and obtained near infrared K_s observations with the CAHA 3.5 m telescope. They also used archival VLA D configuration observations at 1.4 and 5 GHz and archival *Chandra* X-ray observations. [6, 7] identified several possible point-like sources and extended structures that could be related to TeV J2032+4130, although at that time no conclusive results could be obtained.

The *Fermi Gamma-ray Space Telescope* Collaboration reported the existence of a GeV pulsar detected by the Large Area Telescope (LAT) in the region of TeV J2032+4130, namely LAT PSR J2032+4127 [8], compatible in position with the high-energy source 0FGL J2032.2+4122. Recently, [9] have reported GBT observations revealing the presence of a radio pulsar coincident in position and period with LAT PSR J2032+4127. The pulsar has a period of 143 ms and has a dispersion measure of 114.8 ± 0.1 pc cm^{-3}, corresponding to a distance of 3.6 kpc according to the Cordes & Lazio model [10]. This is significantly farther than the ~ 1.7 kpc distance to Cygnus OB2. The period-averaged flux density is 0.12 ± 0.03 mJy at 2 GHz and 0.65 ± 0.13 mJy at 0.8 GHz (spectral index $\alpha = -1.9 \pm 0.4$). A timing solution to both the *Fermi* and the GBT data provides a position of $\alpha = 20^{\rm h}32^{\rm m}13.07 \pm 0.04^{\rm m}$, $\delta = +41^\circ 27' 23.4 \pm 0.2''$ (J2000.0), although timing noise may contribute a systematic error amounting to $1''$. The measured $\dot{P}$ implies a characteristic age of 0.11 Myr and a spin-down luminosity of $\dot{E} = 2.7 \times 10^{35}$ erg s^{-1}. The *Fermi* gamma-ray luminosity is 1.4×10^{35} erg s$^{-1} = 0.5\,\dot{E}$ at 3.6 kpc distance ($0.1\,\dot{E}$ if at 1.7 kpc).

Interestingly, [9] note that the position of PSR J2032+4127 is compatible within errors to that of GMRT 610 MHz source number 5 in [6], which in turn was associated by these authors with a *Chandra* source with $L_{\rm X} \simeq 1.1 \times 10^{31}\ d^2_{1.7\ {\rm kpc}}$ erg s^{-1} [11]. The flux density of GMRT #5 is compatible with the radio spectrum of PSR J2032+4127. In addition, the position of the B0 Ve star MT91 213 is compatible with the positions of all these sources, although it is probably a chance coincidence (see [9] for details). These results suggest the presence of a PWN associated with PSR J2032+4127. This is an ideal candidate to explain the extended TeV source.

2. Multiwavelength study of TeV J2032+4130

To confirm the existence of the PWN and its possible relation with the TeV J2032+4130 source we are currently conducting a multiwavelength analysis to study the putative PWN, its association with PSR J2032+4127, and ultimately to determine if this is the powering source of TeV J2032+4130. Our approach consists of three observational fronts: to conduct arcsecond-resolution radio observations with the VLA to obtain multifrequency images of the region around the pulsar, to conduct a high-resolution VLBI astrometric campaign with the European VLBI Network (EVN) to measure the pulsar proper motion, and to reanalyze *Chandra* observations in order to put in a multiwavelength context the radio observations.

2.1 Very Large Array (VLA)

We performed observations of TeV J2032+4130 with the Karl G. Jansky Very Large Array (VLA) in June 28, 2010 from 09:45 to 13:45 UTC (mean MJD 55375.49). We observed at two frequency bands centered at 4.4 and 7.8 GHz (6.8 and 3.8 cm wavelength, respectively) in D configuration. Each subband had a bandwidth of 128 MHz divided in 64 channels. The amplitude calibrator was 3C48, and J2048+4310 was used as phase calibrator. The data were processed using standard procedures within the CASA software package of NRAO.

2.2 European VLBI Network (EVN)

To measure the proper motion of the *Fermi*/GBT pulsar PSR J2032+4127 we observed it with the EVN at 1.6 GHz in three epochs between 2010 and 2014. The three epochs were recorded at 1024 Mb s^{-1} provided by 16 subbands of 16 MHz each divided in two circular polarizations. J2015+3710 was used as phase reference calibrator, J2007+4029 as an astrometric check source, and 3C345 and J2253+1608 were used as fringe finders. To increase the signal-to-noise ratio of the pulsar detection, we correlated the data using pulsar gating [12]. For the first two epochs the data was correlated at the DiFX correlator in Bonn [13]. The third epoch was correlated at the software correlator at JIVE, because at that time a standard procedure was already available. The pulsar has a period-averaged flux density of 0.18 mJy and a duty cycle of approximately 10% at this frequency. The updated pulsar ephemerids needed to set the gates were obtained through

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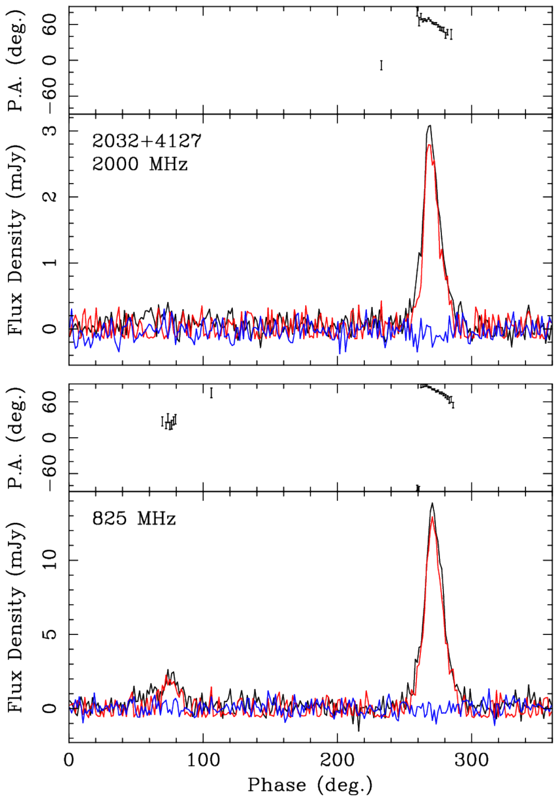

Figure 2: Polarimetric profiles of PSR J2032+4127 based on GBT observations at 2.0 and 0.8 GHz. The black traces correspond to the total intensity, while the red and blue lines correspond, respectively, to linear and circular polarization. Figure from [9].

regular pulsar observations at Jodrell Bank. The faint pulsar was detected in the three epochs, with an improvement of a factor of ~ 2 thanks to the use of pulsar gating. This has provided the first accurate VLBI position of this faint radio pulsar.

2.3 Chandra

Chandra performed a 48.7 ks observation of the field of TeV J2032+4130 on 2004 July 12 with the Advanced CCD Imaging Spectrometer (ACIS) detector. This observation has been previously reported by [11], who report the discovery of several transient and variable sources in the uncertainty region of TeV J2032+4130 and close to it. We have reanalyzed this data in order to put in context the radio observations. We have performed the reduction and analysis with the packages CIAO v4.1.2 and FTOOLS. We have located the point sources in the observation with the task `wavdetect` and excised their source regions from the event list.

3. Summary

The analysis of the available data, and in particular the long-term astrometric project, is still ongoing. The final results of the three types of observations, as well as the conclusions regarding the nature of the putative pulsar wind nebula will be presented in Paredes et al. (in preparation).

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Preliminary images of the VLA data show an extended structure compatible with the position of PSR J2032+4127 and a spectral index compatible with being a pulsar wind nebula. However, the extended radio emission does not overlap with the extended X-ray emission seen in the *Chandra* data. The VLBI astrometric campaign currently contains three observations conducted between 2010 and 2014. One of the observations shows a significant deviation from an straight line. This could be caused by unaccounted ionospheric effects, more severe in at least one of the epochs, or because a constant proper motion cannot describe the pulsar motion, which could be explained if the pulsar is part of a binary system with significant projected size and an orbital period of $\sim$years.

In parallel to the radio and the X-ray observations, we are developing an scenario to explain the extended TeV source as produced by the particles accelerated in the PWN of PSR J2032+4127, including an estimation of the crossing time of the pulsar through the extended radio and the extended TeV emission, and the possible origins of the pulsar.

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