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Low-Frequency Radio Observations of the MGRO J2019+37 Complex

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Abstract. We present here a preliminary account of the results of a wide-field mosaic obtained at 610 MHz (49 cm) with the Giant Metre-wave Radio Telescope (GMRT) in India covering the field of the unidentified TeV source MGRO J2019+37. A catalogue of all radio sources detected has been created including both compact and extended objects. Their observational properties are described and presented. We draw the attention to some peculiar objects inside the $\sim 1^\circ$ uncertainty region of the TeV emission. The possible connection of these sources with the MILAGRO γ-ray emission will be assessed in future work.

1. Introduction

The new generation of Ĉerenkov telescopes, such as H.E.S.S., MAGIC or MILAGRO, has opened a new window in modern high-energy Astrophysics with the discovery in the last years of the galactic very-high-energy (VHE) γ-ray sources. While some of these new sources have been well identified as binaries like LS 5039 or LS I+61 303, nearly one third remain without known counterpart. Taking into account that a significant number of the latter show extended morphologies at 0.1–1° scales in the TeV energy band, the identification of counterparts at lower energies becomes a very difficult task.

Among the VHE γ-ray sources with unknown counterpart, the so far unidentified source TeV J2032+4130 discovered with HEGRA in the direction of the Cygnus OB2 star association Aharonian et al. (2002) can be considered as a prototype. Recent studies have revealed both compact and extended radio sources at arcsecond scales inside the error box of TeV J2032+4130 (Paredes et al. 2007), while XMM-Newton observations have also shown a faint extended X-ray emission Horns et al. (2007a).

The MILAGRO collaboration has very recently reported an addition to the population of extended and unidentified TeV sources with the discovery in the Cygnus region of the most extended TeV source ever known (Abdo et al. 2007a,b). The TeV emission detected in this area spreads over several squared degree, including diffuse emission and the new source MGRO J2019+37, located with an accuracy of $\pm 0.4^\circ$. MGRO J2019+37 is the most significant source detected by MILAGRO, together with the Crab nebula. The Tibet AS-γ experiment has confirmed the detection of this source by finding a 5.8σ signal compatible with the position of MGRO J2019+37 (Wang et al. 2008). On the other hand, VERITAS has observed but not detected the source, placing an upper limit that is compatible with the MILAGRO detection for a hard spectrum extended source Kieda et al. (2008).

The true nature of these emissions is unclear. We do not even know any astrophysical counterpart at lower energies. Despite some authors (Amenomori et al. 2006) have recently proposed a possible connection with anisotropy of the galactic cosmic rays, the TeV γ-ray flux as measured at 12 TeV from the diffuse emission of the Cygnus region (after excluding MGRO J2019+37) exceeds that predicted from a conventional model of cosmic ray production and propagation. This fact strongly suggests the existence of hard-spectrum cosmic ray sources and/or other types of TeV γ-ray sources in the region. Because the lack of detection of a low energy counterpart it has been proposed that hadronic processes instead of leptonic ones could be behind the TeV emission (e.g. Torres, Domingo-Santamaría & Romero 2004).

In order to contribute to the understanding of this peculiar object, we have performed a multiwavelength approach carrying out a deep radio survey at 610 MHz using the Giant Metrewave Radio Telescope (GMRT) interferometer, near infrared $K_{\rm s}$-band using the 3.5 m telescope and the OMEGA2000 camera at the Centro Astronómico Hispano Alemán (CAHA) in Calar Alto, Spain, and archival X-ray observations of some specific fields. We report here an overview of the radio results. The reader is referred to Paredes et al. (2009) for further details.

2. GMRT 610 MHz Radio Survey

Radioastronomers have imaged the Cygnus region at radio frequencies many times, even as part of Galactic surveys. However, these surveys have been carried out with a poor angular resolution and/or a relatively high limiting flux density. Among them, we can quote the Canadian Galactic Plane Survey (CGPS) at 408 and 1420 MHz (Taylor et al. 2003), with angular resolutions of $5.3'$ and $1.6'$ and limiting flux densities of 9 and 1 mJy respectively, at declination of $+40°$; the 327 MHz survey, with an angular resolution of $1'$ and a limiting flux density of 10 mJy (Taylor et al. 1996); and the 408 and 1430 MHz survey, with angular resolution of $3.5' \times 5.2'$ and $1.0' \times 1.5'$ respectively, and limiting flux densities of 150 mJy and 45 mJy respectively (Wendker et al. 1991). The Westerbork Synthesis Radio Telescope (WSRT) 350 and 1400 MHz continuum survey of the Cygnus OB2 association Setia Gunawan et al. (2003), which is the most recent survey of this region, has angular resolutions of $55''$ and $13''$ and limiting flux densities of 10–15 mJy and 2 mJy respectively . Unfortunately, this survey does not cover the MGRO J2019+37 field.

As none of the existing surveys covers the Cygnus region with the resolution and sensitivity that we needed, we aimed to obtain a deep radio map of the field of MGRO J2019+37 with both arc-second detail and sensitivity to extended radio emission.

The GMRT in Pune (India) at the 610 MHz provides a reasonable compromise between angular resolution ($\sim 5''$), mapping of diffuse emission (nearly one-third of baselines have short spacing of $\sim$ a km) and primary beam coverage ($0.8°$) to map a wide area of the sky in a reasonable number of pointings. Therefore, we proposed to conduct a GMRT 610 MHz continuum mini-survey of a region of about $2.5° \times 2.5°$ centered on the MGRO J2019+37 peak of TeV emission ($l= 75°$ and $b= 0°$) and map all radio sources in the field, either compact or diffuse. To conduct the observations, we designed an hexagonal pattern of 19 pointings in order to cover a region of about $2.5° \times 2.5°$ centered on the MGRO J2019+37 peak of emission. This mapping strategy is illustrated in Fig. 1. The observations were carried out in July 2007, but suffered from a series of power failures in the array and additional make-up time was scheduled on August 2007. The whole observation amounted to a total time of 20 hours.

Observations were made in two 16-MHz upper and lower sidebands (USB and LSB) centered on 610 MHz, each split into 128 spectral channels. The data of each side-band were separately edited with standard tasks of the Astronomical Image Processing System (AIPS) package. The sources 3C 286 and 3C 48 were used to set the flux density scale, while phase calibration was performed by repeated observations of the nearby phase calibrator J2052+365. In order to achieve a good *uv* coverage, the observation of each pointing was split into a series of scans. We performed a calibration for a reference channel, and once bad antennas, baselines or channels had been removed, the bandpass correction was used to extend the calibration to all channels. After the bandpass calibration, the central channels of each sideband were averaged, leading to a data file of 5 compressed channels, with a bandwidth small enough to avoid bandwith smearing problems in our images. Standard calibration for continuum data was performed beyond this point. At the end of the self-calibration deconvolution

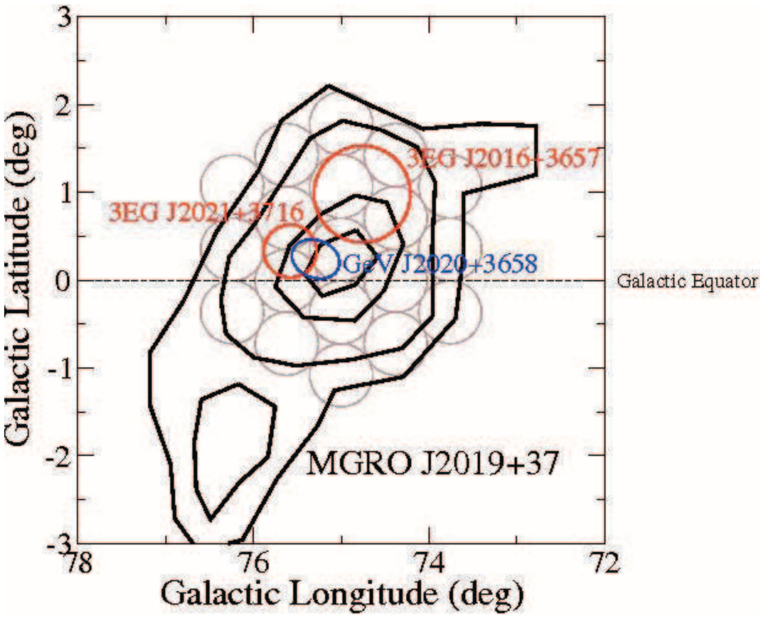

Figure 1. Hexagonal pattern of 19 pointings designed to cover the region of about 2.5°× 2.5° of the TeV source MGRO J2019+37. Superimposed are different EGRET sources (3EG and GeV) that appear in the field.

iteration scheme, we combined both USB and LSB images of each pointing and mosaiced the whole region using the AIPS mosaicing task FLATN.

As we were interested in both compact sources and extended features, we decided to produce different maps from high to low angular resolution of the GMRT mosaic. Our best image has an rms of 0.2 $mJy\ beam^{-1}$ with a $5''$ resolution thanks to the long baselines of the interferometer. In Fig. 2 we show the low angular resolution version as an example. It was produced using a restoring beam of $30''$ in order to better enhance the extended radio sources clearly visible in the field.

In order to produce a catalogue of the detected sources we applied the SExtractor (Bertin & Arnouts 1996) automatic procedure over our $5''$ resolution map, including only sources with peak flux densities higher than about ten times the local noise after primary beam correction. Some of the candidate detections are related with deconvolution artifacts near bright sources, which means that these sources must be removed. After removing objects believed not to be real, the remaining list contains 362 radio sources, 203 fainter than 10 mJy and mostly previously undetected at radio wavelengths. The final version of the catalogue will be available soon (Paredes et al. 2009).

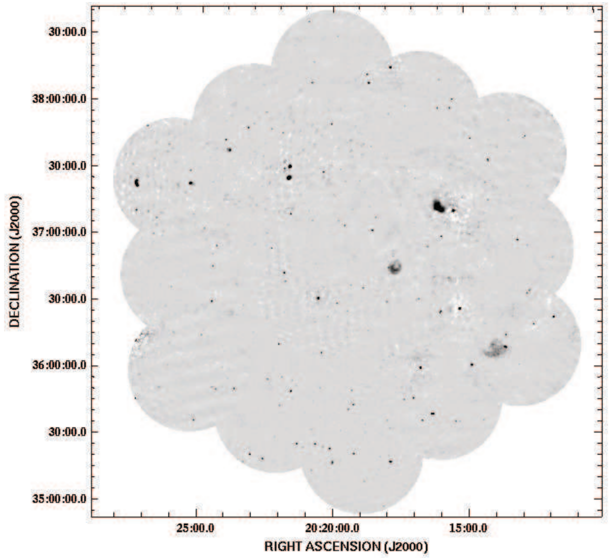

Figure 2. Low-resolution mosaic obtained with the GMRT radio interferometer at 610 MHz. It was produced using a restoring beam of 30″ in order to better enhance the extended radio sources clearly visible in the field.

3. Results

Figure 3 shows the inner part of the low angular resolution radio image of the MGRO J2019+37 field obtained by us. Overlaying the radio map, we have labeled some interesting sources at other wavelengths.

First of all, the location of MGRO J2019+37 is consistent with the EGRET sources 3EG J2016+3657 and 3EG J2021+3716. The blazar-like source known as B2013+370 (G74.87+1.22) (Mukherjee et al. 2000; Halpern et al. 2001) is positionally coincident with the first of them although this blazar is well outside the inner box of MGRO J2019+37. The second is marginally coincident with the pulsar wind nebula G75.2+01 (Hessels et al. 2004). High-energy γ-ray pulsations coming from the pulsar have been detected by AGILE and *Fermi* (Halpern et al. 2008; Abdo et al. 2009). However, we did not find any radio source at this position in our map. From our GMRT data we can only establish an upper limit of 0.9 mJy to any possible point-like counterpart by taking five times the background emission level.

The brightest compact radio source detected within the error box of the TeV peak of emission of MGRO J2019+37 is the source NVSS J202032+363158. Its flux density at 610 MHz is 833 mJy and it has not been resolved. This source appears in the Green Bank 4.85 GHz northern sky surveys (GB6 and 87GB) with a flux density of 121 and 108 mJy respectively. The source has been also detected in the VLA Low-Frequency Sky Survey (VLSS) at 74 MHz (4 m wavelength) with a flux density of 6.4 Jy. We also decided to inspect the NRAO archives and we found a previous VLA snapshot (6 min on source) of this radio source at the 20 cm wavelength in B configuration observed in 25 March 1989. This simple observation was calibrated using standard AIPS tasks also including phase self-calibration. Surprisingly, this radio source is resolved, displaying a one-sided radio jet extending a few arc-sec towards the North, with a core component of ∼250 mJy and a secondary component of about 70 mJy. Based on the flux densities quoted above and assumed to be stable, the radio spectrum of this source can be described by $S_\nu = (523{\pm}2)$ mJy$[\nu/\mathrm{GHz}]^{-0.94\pm0.01}$ and is, therefore, a clear non-thermal emitter.

There is an interesting extended radio source in the field, named Sh 104, which is an optically visible HII region of $7'$ diameter at a distance of 4.0±0.5 kpc. Our GMRT observations reveal a similar structure to that found at 1.46 GHz with the VLA (Fich 1993) and at 1.4 GHz by the NRAO VLA Sky Survey (NVSS) radio continuum survey (Condon et al. 1998). We have computed a crude spectral index map of Sh 104 region by combining matching beams from VLA and GMRT. Despite the poor quality of the resulting map, there are some features with negative spectral index, thus suggesting a non-thermal emission for their radio spectrum.

Finally, there are other interesting sources not obvious at first glance which become evident when looking in detail at each source in the GMRT high angular resolution map. Sources A and B (Fig. 4) reveal themselves as two newly discovered jet-like radio sources located well inside the inner Center of Gravity box of MGRO J2019+37. Their J2000.0 positions are α=$20^{\mathrm{h}}18^{\mathrm{m}}32^{\mathrm{s}}$, δ= $+37^\circ02'30''$ (source A) and α=$20^{\mathrm{h}}19^{\mathrm{m}}48^{\mathrm{s}}$, δ=$+37^\circ06'40''$ (source B). Both sources appear as unresolved in the NVSS catalogue (1.4 GHz) and in the Westerbork 327 MHz survey of the galactic plane (Taylor et al. 1996). Using previous survey detections of these sources and our data, we have estimated their spectral indices as about −1.2 and −0.7 for sources A and B, respectively, thus indicating a non-thermal nature for their radio emission. In the case of source B, its morphology and spectrum is reminiscent of the 'Great Annihilator' 1E 1740−2942, one of the two Galactic Center microquasars (Mirabel et al. 1992).

4. Conclusions, work in progress and future prospects

We have performed a multiwavelength approach to better understand the true nature of the new TeV source MGRO J2019+37, comprising a 610 MHz radio survey, infrared observations in the K_{s}-band and X-ray observations. We have presented here a summary of the preliminary analysis of the radio observations that has very recently been finished. The radio maps show several sources that should be taken into account in order to explain the origin of the emission coming from MGRO J2019+37. The physical understanding of these sources is currently work in progress. We expect to be able to discriminate the likely counterpart of MGRO J2019+37 once all results are put in a multi-wavelength context, together with the near-infrared and X-ray observations.

We intend to make public on the web both the final FITS files and source list of our mini-survey once our main results are published. The final source list will represent a very valuable tool for providing candidate radio counterparts for 3EG J2016+3657, 3EG J2021+3716 and GeV J2020+3658, three unidentified high energy γ-ray sources also in the same field. Moreover, this kind of data for the MGRO J2019+37 field will represent a template database by the time the

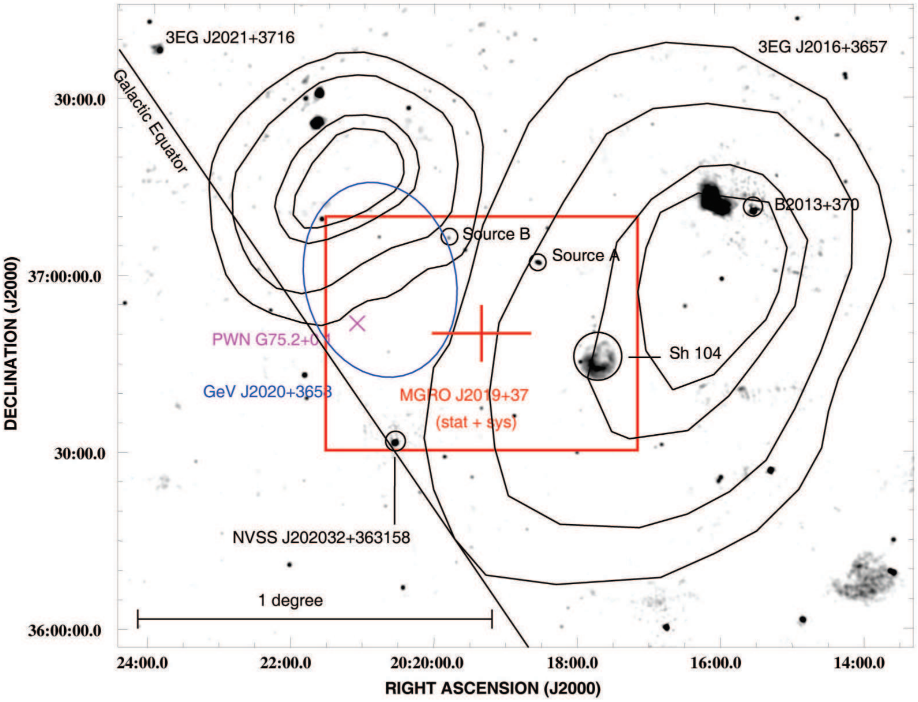

Figure 3. Inner part of the 30″ resolution radio mosaic obtained with the GMRT radiotelescope at 610 MHz showing the Center of Gravity of the TeV emission from the source MGRO J2019+37 and its positional uncertainty including statistic and systematic errors. Countours represent the position of the two EGRET sources, 3EG J2021+3716 and 3EG J2016+3657, consistent with the MGRO J2019+37 position. In addition, we have labelled several radio sources located inside this box which could be responsible of the TeV emission. Sh 104 corresponds to an extended HII region, NVSS J202032+363158 to a bright compact radio source and sources A and B are two newly discovered jet-like sources.

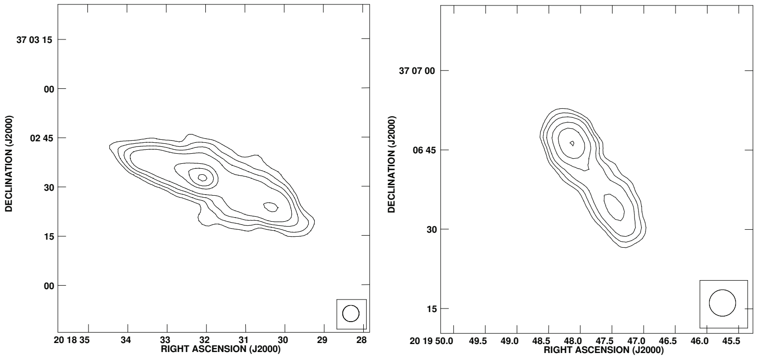

Figure 4. Detailed view of sources A (left) and B (right) discovered inside the ∼ 1° uncertainty region of the TeV emission from the source MGRO J2019+37. Their jet-like morphology and non-thermal nature suggest a possible connection with the γ-ray emission.

Fermi satellite provides more accurate information about the γ-ray sources in this remarkable region of the Galactic Plane.

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