Discovery of a new radio galaxy within the error box of the unidentified $\gamma$-ray source 3EG J1735−1500

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ABSTRACT

We report the discovery of a new radio galaxy within the location error box of the $\gamma$-ray source 3EG J1735−1500. The galaxy is a double-sided jet source forming a large angle with the line of sight. Optical observations reveal a $V \sim 18$ magnitude galaxy at the position of the radio core. Although the association with the EGRET source is not confirmed at the present stage, because there is a competing, alternative $\gamma$-ray candidate within the location error contours which is also studied here, the case deserves further attention. The new radio galaxy can be used to test the recently proposed possibility of $\gamma$-ray emitting radio galaxies beyond the already known case of Centaurus A.

Subject headings: galaxies: active – galaxies: jets – gamma rays: observations – radio continuum: galaxies

1. Introduction

The quest for the identification of the $\gamma$-ray sources detected by EGRET instrument of the Compton Gamma-Ray Observatory is one of the most important challenges of high-energy astrophysics in recent years. Among the 271 sources included in the Third EGRET (3EG) catalog (Hartman et al. 1999) there are a few confirmed pulsars, 66 blazars, and a bunch of miscellaneous identifications including one radio galaxy: the nearby Centaurus A, a Fanaroff-Riley (FR) Type I active galaxy (Sreekumar et al. 1999).

Most identified blazars are strong flat-spectrum radio sources (e.g. only 4 out 46 high-probability blazar detections in Mattox et al. (2001) analysis have fluxes below 1 Jy) with jets

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pointing close to the line of sight. On the contrary, in the case of Centaurus A the viewing angle is rather large (~ 70°, Bailey et al. 1986). Very recently, Mukherjee et al. (2002) have suggested that the radio galaxy NGC 6251 could also be associated with an EGRET source. If this is confirmed it could have important consequences because the spatial density of FR I radio galaxies is far higher than that of blazars, and hence, despite that these objects are expected to be weaker \( \gamma \)-ray emitters, there could be many other unidentified sources associated with them.

In this paper we report the discovery of a new radio galaxy within the location error box of the \( \gamma \)-ray source 3EG J1735–1500. The object was found during a re-analysis of the main sources in the radio field around the position of the EGRET detection. This research is part of a systematic program to study potential low-energy counterparts of unidentified \( \gamma \)-ray sources. Previous results regarding compact radio sources were published by Torres et al. (2001). Here we present the results of a more detailed study and new observations that led to the identification of the new radio galaxy among the potential counterparts of 3EG J1735–1500. We also provide information on all compact radio sources within the EGRET location error box, including spectral index determinations when possible. We have also found that the source PMN J1738–1502 is probably a weak flat-spectrum quasar with mild radio flux, which enhances its probability of being the counterpart of 3EG J1735–1500 respect to the a priori probability estimates by Mattox et al. (2001).

2. Radio data analysis and results

We have used the NRAO VLA Sky Survey (NVSS) (Condon et al. 1998) to study the small-scale radio emission within the inner 95 % location probability contours of the \( \gamma \)-ray source 3EG J1735–1500. Twenty-three radio sources with flux density > 10 mJy at 1.4 GHz have been found, as can be seen in Fig. 1, where we have numbered the sources with increasing galactic longitude. The main characteristics of these sources are listed in Table 2. In particular, we provide, from left to right, the identification number corresponding to Fig. 1, the galactic coordinates, flux density at 1.4 GHz, spectral index (defined in such a way that \( S_\nu \propto \nu^{+\alpha} \)) when observations at other frequencies are available (365 MHz from Douglas et al. 1996 and 4.8 GHz from Griffith & Wright 1993) and the name in other catalogs if any.

With the exceptions of sources no. 8 and 10, all entries in Table 2 correspond to compact objects, at least at the present angular resolution (43″). Source no. 8, which appears as extended in our map, is actually a composite of three different (and probably compact) weak sources listed as no. 7, 8, and 9 in Torres et al. (2001). Source no. 10, instead, is
Fig. 1.— $\gamma$-ray probability contours (50%, 68%, 95% and 99% from inside to outside) of the unidentified source 3EG 1735−1500, with the small-scale 1.4 GHz emission obtained from the NVSS (where radio contours start at 1 mJy beam$^{-1}$). The position of the radio galaxy is marked with a rectangle.
Table 1. Radio sources within the 95\% γ-ray contour.

| #  | Coordinates (l[°], b[°]) | $S_{1.4\,\mathrm{GHz}}$ [mJy] | $\alpha$ | Other ID       |
|----|--------------------------|-------------------------------|----------|----------------|
| 1  | (10.22,+9.34)            | 71.00                         | −1.34    | TXS 1731−153  |
| 2  | (10.23,+9.51)            | 128.96                        | −1.2     | TXS 1730−152  |
| 3  | (10.29,+9.04)            | 32.06                         |          |                |
| 4  | (10.33,+9.21)            | 31.68                         |          |                |
| 5  | (10.39,+9.60)            | 10.88                         |          |                |
| 6  | (10.41,+8.69)            | 177.57                        | −1.04    | TXS 1734−155  |
| 7  | (10.46,+9.53)            | 133.77                        | −0.54    | PMN J1734−1502|
| 8  | (10.53,+9.31)            | 169.72                        | −0.89    | TXS 1732−150  |
| 9  | (10.69,+8.95)            | 24.74                         |          |                |
| 10 | (10.74,+8.85)            | 55.64                         | $\lesssim$0.9 |                |
| 11 | (10.76,+8.65)            | 37.88                         |          |                |
| 12 | (10.84,+9.43)            | 17.07                         |          |                |
| 13 | (10.84,+8.61)            | 46.00                         |          |                |
| 14 | (10.86,+8.91)            | 11.33                         |          |                |
| 15 | (10.94,+9.03)            | 28.62                         |          |                |
| 16 | (10.98,+8.72)            | 330.40                        | −0.17    | PMN J1738−1502|
| 17 | (11.08,+8.68)            | 19.15                         |          |                |
| 18 | (11.11,+9.42)            | 32.44                         |          |                |
| 19 | (11.14,+8.71)            | 10.73                         |          |                |
| 20 | (11.15,+9.72)            | 9.97                          |          |                |
| 21 | (11.19,+9.58)            | 9.63                          |          |                |
| 22 | (11.19,+9.73)            | 25.52                         |          |                |
| 23 | (11.34,+8.76)            | 38.43                         |          |                |
Fig. 2.— **Upper panel:** High-resolution radio image of the galaxy J1737–15 at 1.4 GHz overlapped to the optical image obtained with the Calar Alto 2.2-m telescope using a Johnson’s $I$ filter. Radio contours are shown in steps of 0.6 mJy beam$^{-1}$, starting from 1 mJy beam$^{-1}$. **Lower panel:** An enlargement of the central region of the radio galaxy showing the possible host galaxy. Radio contours are in steps of 0.3 mJy beam$^{-1}$, starting from 1.3 mJy beam$^{-1}$.
really extended. We shall name this source hereafter as J1737−15, according to its radio coordinates. Its morphology at 1.4 GHz (Fig. 2, upper panel) is typical of double-sided FR II radio galaxies. There is a nuclear component as well as two jets ending in large radio lobes. The angular dimensions of J1737−15 are \( \sim 0.04^\circ \times 0.11^\circ \), with an integrated flux of \( 55.6 \pm 1.5 \) mJy at 1.4 GHz. The flux density of the northern component is \( S_{\text{north}} = 21.6 \pm 0.5 \) mJy, whereas the southern one is \( S_{\text{south}} = 30.7 \pm 1.3 \) mJy. The central component has a flux density of \( S_{\text{core}} = 3.80 \pm 0.05 \) mJy, and an estimated J2000.0 ICRS position of \( \alpha = 17^h 37^m 12.9^s \pm 0.3^s \), \( \delta = -15^\circ 11' 02'' \pm 15'' \).

The source is clearly non-thermal since it is not detected at 4.8 GHz (Griffith & Wright 1993). From the 4.8-GHz survey sensitivity we can infer an average steep spectral index \( \alpha \lesssim -0.9 \), but it is not possible to say, within the present resolution, what is the index at the core because of contamination from the radio lobes, which have surely steeper spectra. The general morphology clearly supports the hypothesis of a radio galaxy with jets nearly perpendicular to the line of sight. Should the association between the radio galaxy and the EGRET source be confirmed, J1737−15 would be the second EGRET source (apart Centaurus A) to be detected with a large inclination angle.

3. Optical observations

With the aim of finding the optical counterpart of the radio galaxy we have made \( VR I \) deep photometric observations of J1737−15 on 2002 June 9 at Calar Alto (Almería, Spain) with the 2.2-m telescope of the Centro Astronómico Hispano-Alemán (CAHA). Images were obtained using the Ritchey-Chrétien focus and CAFOS, with a scale factor of 0.53″ per pixel and a 8.8′ × 8.8′ field of view. A series of 600 s images of our target, as well as 200 s images of standard stars from the SA104 field of Landolt (1992), were obtained through the \( V \), \( R \) and \( I \) Johnson filters. The observations were reduced using standard procedures (bias and dark subtraction and flat-field correction) within the IRAF software package. We performed a detailed astrometric reduction of the images using 20 field stars present in the USNO-A2.0 catalog (Monet et al. 1999), with an estimated astrometric accuracy of 0.3″.

We show in Fig. 2 the obtained image through the \( I \) Johnson filter, together with the contours of the radio source from the NVSS. It is clear at first sight the presence of a slightly elongated (east-west) optical object close to the center of the radio source. The fitted J2000.0 ICRS position of this object is \( \alpha = 17^h 37^m 12.744^s \pm 0.021^s, \delta = -15^\circ 11' 01.14'' \pm 0.30'' \), well within the previously obtained error box in position for the core of the radio source. We also obtained absolute photometry of this object, which is believed to be accurate only to \( \pm 0.2 \) magnitudes, because the crowded field around our target prevented a good estimate of the
background. The obtained magnitudes are $V = 18.3 \pm 0.2$, $R = 16.9 \pm 0.2$, and $I = 15.1 \pm 0.2$. Using the galactic extinction estimates from Schlegel et al. (1998), implemented within the NASA/IPAC Extragalactic Database (NED), we obtain a color excess of $E(B - V) = 0.495$ in the direction of J1737−15. However, as pointed out by Arce & Goodman (1999) the values provided by the Schlegel’s model could be overestimated by a factor 1.3–1.5 in regions of smooth extinction with $E(B - V) > 0.15$ mag, as it happens in our case. As a reasonalbe value, we have considered that the NED value is overestimated by a factor $1.3 \pm 0.2$, and used an extinction of $E(B - V) = 0.38 \pm 0.05$. This provides the following extinctions: $A_V = 3.315$ $E(B - V) = 1.3 \pm 0.2$, $A_R = 2.673$ $E(B - V) = 1.0 \pm 0.1$ and $A_I = 1.940$ $E(B - V) = 0.7 \pm 0.1$ (Schlegel et al. 1998). Using these values we obtain the following dereddened magnitudes: $V = 17.0 \pm 0.3$, $R = 15.9 \pm 0.2$, and $I = 14.4 \pm 0.2$. These values imply color indices of $V - R = 1.1 \pm 0.3$ and $R - I = 1.5 \pm 0.3$ (where the errors have been computed directly from the uncertainties in measured magnitudes and assumed $E(B - V)$).

If we suppose that this optical object is a star, the ranges of obtained dereddened colors only allow possibilities such as M3III or M0I, according to Ducati et al. (2001). However, comparison of the obtained apparent dereddened visual magnitude with the expected absolute visual magnitude (Wainscoat et al. 1992) implies distances of 33 and 465 kpc, respectively. The second value is unrealistic, while the first one implies a galactic height ($b = 9.2^\circ$) of $\sim 5$ kpc, in clear disagreement of what is typically found for M3III stars. Therefore, the dereddened colors are clearly incompatible with the object being a single galactic star located by chance in the same direction of the radio galaxy core.

On the other hand, since the source is elongated, a 2-D Gaussian fit can provide information about the ellipticity and position angle. We have performed several Gaussian fits using different fitting box sizes. In all cases the ellipticity of the source seems to be around 0.14, while the position angle changes from $85^\circ$ (counterclockwise from north) to $75^\circ$ when reducing the size of the fitting box. In any case, the object is extended practically in the east-west direction, i.e., perpendicular to the radio jets. All these facts suggest that our identified optical counterpart is a galaxy, at the center of which the jets visible at radio wavelengths are produced.

In addition to the optical counterpart we have looked for infrared and X-ray sources at the position of J1737−15. Filtered IRAS images (Wheelock et al. 1991) at 12 and 100 microns of the region show no particular infrared enhancement at the central position of the radio galaxy. The ROSAT All-Sky Survey (0.1–2.4 keV) shows three X-ray sources inside of the $\gamma$-ray 95% contour but none of them is close to J1737−15.
Fig. 3.— The $\gamma$-ray history of 3EG J1735$-$1500. Boxes indicate source detections as opposed to upper limits.
4. Discussion

Depending on the jet and ambient medium parameters, most double-sided radio sources have sizes below $\sim 300$ kpc (Begelman et al. 1984). In the case of the radio galaxy reported here, and using standard Friedmann-Robertson-Walker formulae, this size translates into a possible distance smaller than 350 Mpc. If 3EG J1735−1500 is indeed the result of $\gamma$-ray emission in J1737−15, the intrinsic luminosity at $E > 100$ MeV, at the distance quoted, should be smaller than $2 \times 10^{44}$ erg s$^{-1}$, although mild beaming could reduce this figure. A correct determination of the distance requires a knowledge of the redshift that is still unknown. The information we provide here for the optical counterpart will be useful to guide future spectroscopic observations. As in the case of Centaurus A and 3EG J1621+8203, the luminosity needed to generate the $\gamma$-ray source observed is several orders of magnitude less than those required for typical EGRET blazars ($10^{45}−10^{48}$ erg s$^{-1}$).

The $\gamma$-ray variability history of 3EG J1735−1500 is shown in Fig. 3. The source was detected only in three EGRET viewing periods (VPs) –in the remaining VPs only upper limits to the flux were established– and appears to be variable. Torres et al.’s (2001) index $I$ gives $I = 8.86$, which place this source as one of the most variable gamma-ray sources in the EGRET catalog. Tompkins’ (1999) index $\tau$ is $\tau = 1.09^{+0.10}_{-0.00}$, which, although inconclusive due to its lower limit, the central value and upper limit of the index also place this source as one of the most variable ones in the Catalog. (For a detailed discussion on variability indices see Torres, Pessah and Romero 2001). The likely variability status of this source might imply that the $\gamma$-ray emission is produced in the central region and not in the extended lobes, if related with the discovered radio galaxy. The photon spectral index seems to be unusually steep with a value $\Gamma = 3.24 \pm 0.47$, steeper than the average of the $\gamma$-ray blazars spectra, a property also shared by Centaurus A and 3EG J1621+8203.

Since 3EG J1735−1500 is at a low galactic latitude it could be possible that some galactic object not visible at radio wavelengths be responsible of the high-energy emission. However, the source is not coincident with early-type stars, OB associations, or galactic X-ray binaries (Romero et al. 1999).

The only other known potential counterpart in addition to the galaxy discussed here is the source PMN J1738−1502. It is a compact radio source with a total flux at 1.4 MHz of $\sim 0.3$ Jy (source no. 16 in Table 2). We have calculated for this object a flat spectral index $\alpha = -0.17$, which makes of it a clear blazar candidate. Mattox et al. (2001) give an a priori probability of only 0.07 % for a physical association. The a posteriori probability (see Mattox et al.’s paper for details) is slightly higher but still very small: 0.35 %. The radio source is weaker than most high-probability $\gamma$-ray blazars, but similar to most plausible (i.e. with lower a priori probability) identifications. Consequently, this source should be considered
a serious alternative counterpart of the EGRET source despite the low probabilities given by Mattox et al. (2001). The object is similar to the plausible identification proposed recently by Wallace et al. (2002) in the case of 3EG J2006−2321, although we notice that in the case of 3EG J1735−1500 the high-energy photon index is far softer ($\Gamma = 3.24 \pm 0.47$ vs $\Gamma = 2.47 \pm 0.44$). Since $\gamma$-ray blazars tend to be highly polarized and variable, we are planning optical polarization observations of this source in order to confirm its blazar nature.

One of the main problems to explain the synchrotron emission in radio galaxies is that this radiation is distributed rather uniformly along distances $\sim 100$ kpc. To explain how the continuous acceleration of electrons take place in these huge sources remains as one of the most difficult topics in jet theory. Recently, it has been suggested by Neronov et al. (2002) that in some cases the relativistic leptonic population can be locally created by very-high energy $\gamma$-rays produced at the central source and injected into the jet, where they produce pairs through interactions with the 2.7 K cosmic background radiation. In this scenario lower energy (GeV) photons would escape from the radio galaxy and could even traverse the diffuse infrared background without further interaction reaching the Earth. The $\gamma$-rays could be produced in the central engine by photon-pion process involving disk photons (Neronov et al. 2002). Future multifrequency observations of J1737−15 could help to test the proposal of an association with 3EG J1735−1500. If the high-energy emission is confirmed, this radio galaxy could become an important natural laboratory to test the theories of non-thermal emission in extragalactic jet sources.

5. Conclusions

We have discovered a new radio galaxy inside the error box of the $\gamma$-ray source 3EG J1735−1500. It is a double-sided FR II type of object. Its linear angular size implies that it is relatively nearby. We have also identified the host optical galaxy, which appears elongated in a direction perpendicular to the radio structure. Future spectroscopic observations will help to fix the distance to this object. If it turns out to be closer that 100 Mpc, the radio galaxy could be a potential acceleration site of ultra-high energy cosmic rays, avoiding the so-called Greisen-Zatsepin-Kuz’min (GZK) cut-off (see Rachen & Biermann 1993).

We have also study the other important likely potential counterpart of 3EG J1735−1500. We have found that it is a flat-spectrum compact radio source, possibly a blazar, and hence perhaps a $\gamma$-ray emitting object. The remaining sources within the location confidence contours of the EGRET detection seem to be uninteresting from the point of view of the high-energy emission. Forthcoming observational studies of these two objects will shed light on the real nature of 3EG J1735−1500.
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