

Is 3C 111, an apparently normal radio galaxy, the counterpart of 3EG J0416+3650?

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Abstract. The Third EGRET Catalog (3EG) lists 66 high-confidence identifications of sources with Active Galactic Nuclei (AGN). All are classified as belonging to the blazar class, with the only exception of the nearby radio galaxy Centaurus A. We report and strengthen the association of another radio galaxy, 3C 111, with the EGRET source 3EG J0416+3650. At the time of the compilation of the 3EG catalogue, 3C 111 has been considered as a low-confidence counterpart of 3EG J0416+3650, being located outside the 99% γ -ray probability contour. Since this first suggestion, no other counterparts have been reported nor the EGRET error box has been searched for likely candidates. 3C 111 has never been considered or cited in literature as a radiogalaxy counterpart of an EGRET source. We report a detailed multiwavelength study of the EGRET error box as well as for the first time the overall spectral energy distribution of 3C 111, which appears to be intriguingly similar to those of blazars, suggesting that the radiogalaxy 3C 111 is the likely counterpart of 3EG J0416+3650.

Key words. gamma rays: observations – X-rays: individuals: 3EG J0416+3650 – X-rays: general

1. Introduction

The identification of sources detected by EGRET is one of the great challenges of current gamma-ray astronomy. More than sixty percent of the 271 high energy gamma-ray sources reported in the 3rd EGRET Catalogue (Hartman et al. 1999) are unidentified, with no firmly established counterparts at other wavebands. The majority of the identified objects are of extragalactic origin and belong to the blazar type. The 3EG catalogue lists 66 high-confidence identifications of blazars (labelled as “A”) and 27 lower-confidence identifications (labelled as “a”). These objects have high and variable gamma-ray luminosities (often dominating the bolometric power) and power law spectra with an average index of $\Gamma = 2.15 \pm 0.04$ (Mukherjee et al. 1997). Most of the EGRET blazars are strong radio sources (only a small fraction have a 5 GHz flux below 1 Jy) with flat spectra ($\alpha \leq 0.5$, $S_\nu \propto \nu^{-\alpha}$). They also show significant optical polarization and/or variability in various wavebands; superluminal motion has been observed in some cases.

The combination of all these characteristics support the argument of relativistic beaming in jets which are pointing close to the line of sight. In the widely adopted scenario of blazars, a single population of high-energy electrons in a relativistic jet radiate from the radio/FIR to the UV- soft X-ray by the synchrotron process and at higher frequencies by inverse Compton scattering soft-target photons present either in the jet (synchrotron self-Compton [SSC] model), in the surrounding

ambient (external Compton [EC] model), or in both (Ghisellini et al. 1998, and references therein). Therefore in the blazar SED, two peaks corresponding to the synchrotron and inverse Compton components should be evident.

Very recently, attention has been focussed on the possibility that radio galaxies could be also counterparts of unidentified EGRET objects. For example, Centaurus A (a Faranoff-Riley type I radiogalaxy) is the closest AGN ($z = 0.0018$), and the only radio galaxy positively detected by EGRET (Sreekumar et al. 1999). Its gamma-ray spectrum is well characterized by a single power law of photon index 2.4 ± 0.28 , steeper than the usual blazar-like γ -ray source, while the luminosity is $\sim 10^{41}$ erg s⁻¹, about 10⁵ time less than that typically observed by EGRET. The nucleus of Centaurus A has a 5 GHz flux greater than 1 Jy and a flat radio spectrum (Burns et al. 1983) plus a SED similar to that of blazars (Chiaberge et al. 2001). Its jet is offset by an angle of $\sim 70^\circ$ from the line of sight (Bailey et al. 1986; Fujisawa et al. 2000). There are three additional EGRET sources, for which a possible radio galaxy counterpart has been suggested. One such source is 3EG J1621+8203 (Mukherjee et al. 2002) for which NGC 6251 (a Faranoff Riley type I radio galaxy) is the likely counterpart. Combi et al. (2003) have also recently reported the discovery of a double-sided Faranoff-Riley type II radio source, J1737-15, in the error box of 3EG J1735-1500; in this case, however, the association with the EGRET source is more controversial due to the presence in the error box of another likely candidate. Also in these two cases, the EGRET spectrum is steeper

and the gamma-ray luminosity lower than typically observed in blazars. Both sources have a flux at or around 5 GHz lower than 1 Jy (0.36 Jy for NGC 6251 while J1735-1500 is not detected), a nuclear radio spectrum which is flat in NGC 6251 (Jones et al. 1986) and steep in J1735-15 (Combi et al. 2003); only in the case of NGC 6251 there are enough data in the literature to show that the nuclear SED is similar to blazars (Chiaberge et al. 2003). The radio jet of NGC 6251 makes an angle of 45° with the line of sight (Sudou & Taniguchi 2000) and the γ -ray luminosity in this case is 3×10^{43} erg s^{-1} . Compared with Cen A, the greater distance to NGC 6251 could, perhaps, be compensated by a smaller angle between the jet and the line of sight. More recently the possible association of the Seyfert 1 galaxy GRS J1736-2908 with 3EG J1736-2908 has also been proposed (Di Cocco et al. 2004). This AGN is not a strong radio emitter having a flux density at 5 GHz and 1.4 GHz of respectively ≈ 23 mJy and ≈ 59 mJy and its radio spectrum is described by a power law with $\alpha = 0.75$, which however does not fulfill the requirement of flatness ($\alpha \leq 0.5$, $S_\nu \propto \nu^{-\alpha}$).

To summarize the sparse observational evidence available at the moment indicate that if radio galaxies are counterparts of EGRET sources, the characteristics are still similar to blazars but the source is of lower intensity; this suggests the possibility that we are dealing with objects where the jet is misoriented with respect to the observer. Recently Ghisellini et al. (2004) have put forward a structured jet model in which a slow jet layer is cospatial to a fast jet spine. In this model there will be a strong radiative interplay and feedback between the layer and spine as both parts see extraphotons coming from the other part: this enhances the inverse compton emission of both components thus explaining why also some radio galaxies can be relatively strong in γ -rays.

Here we present arguments in favour of the association of yet another radio galaxy, 3C 111, with an EGRET source, 3EG J0416+3650. This result makes the probability for radio galaxies to be counterparts of unidentified EGRET sources even stronger and the search more promising given their much higher spatial density with respect to blazars. This could have important consequences in terms of the AGN contribution to the gamma-ray background and the relation between aligned and misaligned blazars in terms of emission mechanisms, AGN unified theory and jet physics.

2. The gamma-ray source

3EG J0416+3650 is a gamma-ray source located at $l = 162.2$ $b = -9.97$ (i.e. close to the galactic plane), with a 95% confidence error radius of $38'.2$ (Hartman et al. 1999). More recently Mattox et al. (2001) have generated elliptical fits to the 95% contours of the source: the semimajor and semiminor axes are $44'.6$ and $32'.5$ respectively with a position angle for the semimajor axis of 167° .

In the third EGRET catalogue the source is labelled as confused (“C”) due to the presence of 4 nearby sources all having gamma-ray fluxes greater than 3EG J0416+3650. The presence of these nearby sources can have an effect on the reported position and related uncertainty, so that some allowance in the

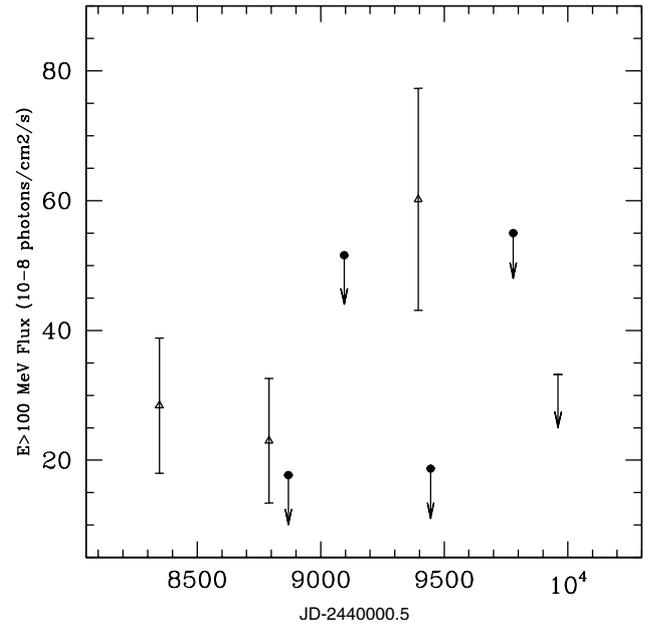


Fig. 1. Light curve of 3EG J0416+3650 from April 1991 to September 1995.

countour errors should be considered to account for this systematic effect (Hartman et al. 1999, Sect. 5).

3EG J0416+3650 was not always bright enough to be detected by EGRET. In fact the source does not appear in the second catalogue while in the third one the source has been detected only in three Viewing Periods or VPs ($VP = 0.2+$, from 1991 April 22 to 1991 May 07; $VP = 31.0$, from 1992 June 11 to 1992 June 25; $VP = 321+$, from 1994 Feb. 8 to 1994 Feb. 17); in the remaining VPs only upper limits to the flux were established. In the cumulative exposure from multiple Viewing Periods ($VP = 1234$, from 1991 April to 1995 October) the source is reported with a significance of 5.3σ and with an average flux above 100 MeV of 1.3×10^{-7} photon $cm^{-2} s^{-1}$. The gamma-ray spectrum is well fitted by a simple power law with photon index $\Gamma = 2.59 \pm 0.32$ steeper than that generally observed in EGRET blazars and pulsars, which are by far the most obvious counterparts of unidentified gamma-ray sources.

The EGRET light curve from the beginning to the end of the mission obtained from the 3EG catalogue (Hartman et al. 1999) suggests variability of the gamma-ray flux (see Fig. 1). In fact Torres et al. (2001) have measured a variability parameter of $I = 2.61$ for this source, slightly higher than the value of 2.5 which is 3σ away from the standard value of pulsars generally considered non variable. More recently Nolan et al. (2003) re-evaluated the variability of all EGRET sources by a different method and measured for 3EG J0416+3650 a variability index δ of 0.59. This value is significantly larger than the fractional variability expected from steady sources, $\delta < 0.14$, thus confirming Torres et al. results.

Hartman et al. (1999) first suggested 3C 111 ($z = 0.0485$) as the optical counterpart of the EGRET source; but since the source optical position is outside the 99% contour this radio galaxy has been considered as a low confidence

counterpart (type “a” in the 3EG catalog). Mattox et al. (2001) estimated the a priori probability of association to be 0.2 and the a posteriori to be 0.019, just slightly higher than the minimum value (0.01) suggested for standard consideration of a potential identification. The low value obtained is due to the large distance of 3C 111 from the EGRET position (~ 76 arcmin) and to a radio spectrum between 20 cm and 6 cm (Mattox et al. 2001) which did not fulfill the requirement of flatness. Since this first suggestion, no other counterparts have been reported nor the EGRET error box has been searched for likely candidates. 3C 111 has never been considered or cited in literature as a radio galaxy counterpart of an EGRET source.

3. Search for X-ray/radio counterparts in the EGRET error box

As discussed above, the EGRET positional uncertainty is large and not always fully reliable and this makes optical identification on the basis of position alone quite difficult. Other methods for identifying counterparts of EGRET objects have relied on information at other wavebands, particularly in the radio, looking for strong flat spectrum radio sources and/or in X-rays, searching for high energy emitting objects. Following this line, we have started a program to look for high energy (above 10 keV) emitting sources located within EGRET error boxes via available high energy telescopes such as BeppoSAX (Sguera et al. 2004) and INTEGRAL. In Fig. 2 the MECS (2–10 keV) image of the BeppoSAX observation targeted at 3C 111 is superimposed on the EGRET γ -ray probability contours (50%, 68%, 95%, 99% and 99.9%). We note that 3C 111 is located between the 99% and 99.9% contours.

The cross correlation of the 99.9% EGRET error box with the Rosat All-Sky-Survey catalogues (Bright B and Faint F) have resulted in 12 objects (1 and 11 respectively); furthermore there is an Einstein Slew Survey source (ESS) which is not related to any of the Rosat sources. Therefore all together there are 13 X-ray sources within the EGRET error box and they are shown in Fig. 2 by means of different symbols. All these soft X-ray candidates are listed in Table 1 together with their coordinates, their Rosat/Einstein count rates and the offset from the 3EG source position. The only source reported in the Rosat Bright source catalogue is 3C 111. All other X-ray objects are either stars or unidentified in the Simbad/NED databases. Only one X-ray source, 3C 111, is detected at energies greater than a few keV. Apart from this active galaxy, the unidentified Einstein Slew Survey source 1ES0414+365 (No. 13 in Table 1) is the only other X-ray source in the field for which there might be reasons to consider it as a possible counterpart. It is a bright X-ray source (only a factor ~ 1.4 dimmer than 3C 111 in the 0.2–3.5 keV), it is likely to be a transient (as was not observed by other X-ray instruments) and it is the closest to the EGRET position (see Fig. 2). However, lacking information on its spectral shape (especially above a few keV) and nature, it is difficult at this stage to speculate further on its possible association to the EGRET source.

A cross correlation of all these X-ray objects with the radio catalogues available in the HESARC database indicates that only one object is radio emitting: 3C 111 (see Table 2 for

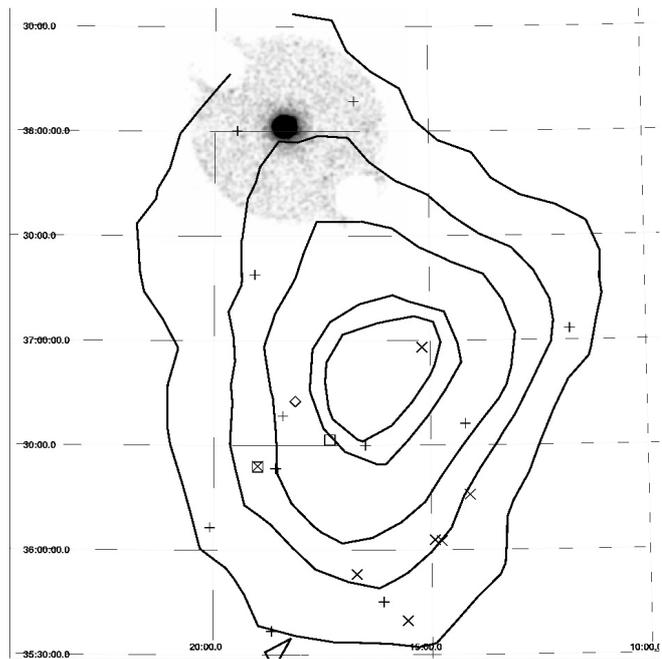


Fig. 2. The BeppoSAX-MECS (2–10 keV) image superimposed on the EGRET γ -ray probability contours at 50%, 68%, 95%, 99% and 99.9% confidence level. All sources listed in Tables 1 and 3 are shown: crosses are ROSAT Faint sources, diamond is Einstein Slew Survey source, pluses are NVSS radio sources and squares are Green Bank radio sources.

details). To further investigate possible radio counterparts of the EGRET source, we have searched the NRAO/VLA sky survey (NVSS) catalog (Condon et al. 1998) for possible 1.4 GHz (20 cm) objects within the EGRET 99.9% error contours. There are 8 sources with an integrated radio flux ≥ 100 mJy (see pluses in Fig. 2) and they are all listed in Table 3 together with their coordinates, fluxes and the offsets from the 3EG source position. The brightest one (NVSS J041820+380148, No. 8 in Table 3) coincides again with 3C 111. Note the close position of sources Nos. 4 and 5, which suggests a likely association; in fact source n.5 is identified in NED with a symmetric double so that No. 4 could be part of this source. Except for 3C 111, no X-ray emission is detected at the position of these radio emitting sources and again NED reveals that most of them have steep radio spectra. The most effective way to look for radio candidates of gamma-ray sources is by searching high frequency catalogues which are more likely to isolate flat spectrum sources. Using the Green Bank Radio Source Catalog at 6 cm (Becker et al. 1991) we found three radio sources inside the 99.9% EGRET γ -ray probability contours (see squares in Fig. 2) having flux greater than 100 mJy (see Table 3). By far the brightest one is GB6 J0418+3801 (No. 9 in Table 3) which coincides with 3C 111. The GB radio source No. 11 is the only likely flat spectrum object in the error box (apart 3C 111): combining the 4.85 GHz measurement with 20 cm data we obtain a radio spectrum with $\alpha = -1.09$ ($S_\nu \propto \nu^{-\alpha}$). Nevertheless this radio source and the other one (No. 10 in Table 3) have no X-ray counterpart and are too dim in radio to be considered potentially likely counterparts.

Table 1. X-ray sources in the EGRET error box.

| | Source | RA (J2000) | Dec (J2000) | Count rate Cts/s | Search offset arcmin | Type | Radio Count. |
|----|--------------------------|---------------|----------------|---------------------|-------------------------|------------------|--------------|
| 1 | 1RXS J041821.6+380134 | 04 18 21.6 | +38 01 34.5 | 0.160 | 77.95 | B | Yes |
| 2 | 1RXS J041630.5+362957 | 04 16 30.5 | +36 29 57.5 | 0.039 | 18.42 | F | No |
| 3 | 1RXS J041412.2+363611 | 04 14 12.2 | +36 36 11.0 | 0.016 | 26.76 | F | No |
| 4 | 1RXS J041824.5+363827 | 04 18 24.5 | +36 38 27.5 | 0.013 | 28.21 | F | No |
| 5 | 1RXS J041834.7+362325 | 04 18 34.7 | +36 23 25.5 | 0.022 | 37.74 | F | No |
| 6 | 1RXS J041903.8+371856 | 04 19 03.8 | +37 18 56.5 | 0.010 | 46.18 | F | No |
| 7 | 1RXS J041145.6+370315 | 04 11 45.6 | +37 03 15.0 | 0.027 | 53.66 | F | No |
| 8 | 1RXS J042005.2+360630 | 04 20 05.2 | +36 06 30.5 | 0.016 | 65.23 | F | No |
| 9 | 1RXS J041605.8+354510 | 04 16 05.8 | +35 45 10.5 | 0.019 | 65.60 | F | No |
| 10 | 1RXS J041645.0+380837 | 04 16 45.0 | +38 08 37.5 | 0.027 | 78.20 | F | No |
| 11 | 1RXS J041928.8+380010 | 04 19 28.8 | +38 00 10.5 | 0.014 | 80.14 | F | No |
| 12 | 1RXS J041840.0+353649 | 04 18 40.0 | +35 36 49.0 | 0.016 | 80.15 | F | No |
| 13 | 1ES0414+365 [†] | 04 18 07.4 | +36 42 36.0 | 0.300 | 23.74 | ESS [‡] | No |

Note: [†] energy range counts rate is 0.2–3.5 keV.

Note: [‡] Einstein Slew Survey.

Table 2. Radio counterparts of 3C 111.

| | Source | Flux mJy | Radio catalog |
|---|---------------------|-------------|-------------------------------|
| 1 | NVSS J041820+380148 | 7726 | NRAO VLA Sky Survey (20 cm) |
| 2 | GB6J0418+3801 | 5168 | Green Bank 6 cm survey (6 cm) |
| 3 | 0415+3754 | 6637 | 6cm Radio Catalog (6 cm) |
| 4 | WN 0415.0+3754 | 12 959 | Westerbork Sky Survey (92 cm) |
| 5 | TXS 0414+378 | 14 017 | Texas Survey (82 cm) |

Table 3. Radio sources in the EGRET error box.

| | Source | RA (J2000) | Dec (J2000) | Flux mJy | Search offset arcmin |
|----|---------------------|---------------|----------------|-------------|-------------------------|
| 1 | NVSS J041511+365802 | 04 15 11.2 | +36 58 02.8 | 260.8 | 15.78 |
| 2 | NVSS J041406+361548 | 04 14 06.4 | +36 15 48.4 | 110.8 | 40.89 |
| 3 | NVSS J041859+362402 | 04 18 59.3 | +36 24 02.3 | 420.5 | 41.26 |
| 4 | NVSS J041455+360250 | 04 14 55.1 | +36 02 50.7 | 103.7 | 47.73 |
| 5 | NVSS J041445+360236 | 04 14 45.9 | +36 02 36.2 | 127.8 | 48.59 |
| 6 | NVSS J041642+355303 | 04 16 42.8 | +35 53 03.1 | 111.8 | 55.29 |
| 7 | NVSS J041533+353940 | 04 15 33.2 | +35 39 40.7 | 218.9 | 71.42 |
| 8 | NVSS J041820+380148 | 04 18 20.9 | +38 01 48.6 | 7726 | 75.85 |
| 9 | GB6J0418+3801 | 04 18 22.1 | +38 01 47.0 | 5168 | 75.93 |
| 10 | GB6J0417+3631 | 04 17 19.6 | +36 31 36.0 | 123.0 | 24.10 |
| 11 | GB6J0418+3623 | 04 18 59.4 | +36 23 53.0 | 112.0 | 43.84 |

To conclude, 3C 111 is not only the strongest hard X-ray source in the EGRET error box but it is also by far the brightest radio object in the vicinity of 3EG J0416+3650.

4. BeppoSAX observations of 3C 111

BeppoSAX-NFI pointed at 3C 111 in March 1998, for an effective MECS and PDS exposure time of 69 Ks and 33 Ks

respectively. MECS data have been downloaded from the BeppoSAX archive and a standard analysis was performed using SAXDAS software. The PDS spectra were instead extracted using the XAS v2.1 package (Chiappetti & Dal Fiume 1997) which allows a more reliable check of the background fields. For the PDS data we selected visibility windows, following the criteria of No Earth occultation and high voltage stability during the exposure; in addition observations closest to the

South Atlantic Anomaly were discarded from the analysis. A careful analysis of the +OFF –OFF field was also performed in order to check for the presence of contaminating sources, which if present would provide an uncorrect background subtraction; no contamination has been found despite the location of these offset fields in the galactic plane region. Spectral fits were performed using the XSPEC 11.0.1 software package and public response matrices as from the 1998 November issue. MECS PI (Pulse Invariant) channels were rebinned in order to sample the instrument resolution with an accuracy proportional to the count rate. The PDS data were instead rebinned so as to have logarithmically equal energy intervals. The data rebinning is also required to have at least 20 counts in each bin such that the $\Delta\chi^2$ statistics could be reliably used. In the following analysis, we use an absorbed component to take into account the galactic absorption that in the direction of 3C 111 is $\sim 1.2 \times 10^{22} \text{ cm}^{-2}$, if we consider both the molecular and neutral hydrogen column density (Bania et al. 1991). The quoted errors in the following correspond to 90% confidence level for one interesting parameter ($\Delta\chi^2 = 2.71$).

3C 111 is well detected in the 2–10 keV energy range at 125σ (see Fig. 1 where the MECS image has been superimposed on the EGRET countours). At higher energy, in the PDS regime, a 10.5σ detection is also measured.

A fit to the combined MECS/PDS data sets provides a value of $0.81^{+0.13}_{-0.11}$ for the cross calibration constant between the two instruments, fully compatible within the errors with the nominal range expected (Fiore et al. 1998). The broad band (2–200 keV) spectrum of the source provides a power law with a hard photon index of $\Gamma = 1.64^{+0.056}_{-0.056}$. Neither a reflection component nor an iron line is required by the data and there is no evidence in the data for absorption in excess to the galactic value. Furthermore the BeppoSAX spectrum does not show evidence for a high energy break up to about 200 keV. Overall we conclude that the X-ray power law is free from extra features (absorption, reflection, line, cutoff), i.e. is blazar like. The fluxes corrected for absorption are respectively 2.7×10^{-11} and $9 \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$ for the 2–10 and 15–200 keV band; the corresponding luminosities (at the reported redshift and assuming $H_0 = 75$, $\lambda_0 = 0.7$) are respectively 1.3×10^{44} and $4.2 \times 10^{44} \text{ erg s}^{-1}$.

5. 3C 111 as a misaligned blazar

3C 111 is a near ($z = 0.0485$) Fanaroff-Riley (FR) type II radio source and displays several small-scale features characteristic of a highly active nucleus.

The bright and variable central component is coincident with a broad line galaxy classified as a Seyfert 1 (NED). Few morphological details are known of the optical galaxy since it is behind a heavily obscured region identified with the galactic dark cloud complex Taurus B. (Ungerer et al. 1985). It is a very small and elliptical-like galaxy strongly dominated by a bright point like nucleus with a very faint underlying fuzz.

The radio morphology is typical of FR II objects with a double-lobe/single jet structure (Linfield & Perley 1984). On kiloparsec scales, the one sided highly collimated jet is seen emerging from the core at a position angle of $\sim 63^\circ$ and leading

to the spot at the edge of one of the two lobes; there is probably an active but undetected counterjet feeding the other lobe. On parsec scales, the jet is much more prominent and is roughly aligned with the kpc jet (Linfield 1981). The central component is strongly variable on a time scale of a few months: high resolution observations at 6 cm show dramatic changes in the structure of the compact emission region implying superluminal behaviour (Preuss et al. 1988, 1990). The radio spectrum of 3C 111 is flat having an index of -0.3 ($\alpha \geq -0.5$, $S_\nu \propto \nu^\alpha$) from 6 cm to 80 cm (Becker et al. 1991).

In the mm band, 3C 111 has the strongest compact core of all FR II radio galaxies. The spectrum between 4 cm and 3 mm is flat or inverted (Bloom et al. 1994). At times 3C 111 displays superluminal structural changes and/or strong mm outbursts. A large outburst, with flux values $>10 \text{ Jy}$ at 3.3 mm, was discovered with IRAM interferometer in January 1996 (Alef et al. 1998). Reich et al. (1993) have shown that hard γ -ray emission from EGRET blazars is associated with high and variable mm flux densities. During March 1991 and July 1992 (close to the EGRET Viewing Period respectively $VP = 0.2+$ and $VP = 31.0$) 3C 111 has been observed at 3.3 mm wavelength (Steppe et al. 1993), showing high flux densities (respectively 3.6 Jy and 3.2 Jy).

In the far-infrared, 3C 111 is a strong emitter detected by IRAS (Golombek et al. 1988). 2MASS measurements are also available (band *J, H, K*) from the HEASARC database.

In the X-ray band the source has been observed by every major instrument. The long term behaviour of the source suggest at least a factor of 5 variation in the 2–10 keV range (Reynolds et al. 1998), while no significant fluctuations on time scales less than an hour have been observed (Eracleous et al. 2000).

As for the γ -ray band, 3C 111 has not been detected by COMPTEL (Maisack et al. 1997) placing 2σ upper limits on its emission at energies 0.75–1 MeV, 1–3 MeV, 3–10 MeV. Furthermore, assuming that 3C 111 is the counterpart of 3EG J0416+3650, EGRET measurements at energies $E > 100 \text{ MeV}$ are also available (Hartman et al. 1999).

To conclude several pieces of evidence point to the idea that 3C 111 is a blazar like object: it is a flat spectrum radio source with a strong radio core strongly polarized, it is a strong millimeter emitter, it is a superluminal source and shows strong variability in every wavebands where it has been monitored; furthermore the X-ray spectrum is blazar like lacking all features due to reprocessing emission.

To confirm this behaviour we have also constructed the source SED collecting, from the literature and from the BeppoSAX results presented in this paper, fluxes spanning the widest range of frequencies, from the radio to the gamma-ray band. These data produce the observed SED shown in Fig. 3, which appears to be composed of two broad peaks, their maxima occur in spectral bands which are essentially unaffected by dust/gas absorption (respectively far-infrared and soft gamma-ray range). However absorption must be taken into consideration, especially in view of the location of 3C 111 behind the Taurus cloud complex: absorption would indeed naturally steepen the Infrared to UV and soft to hard X-ray slopes of the continuum emission thus artificially producing a two peak

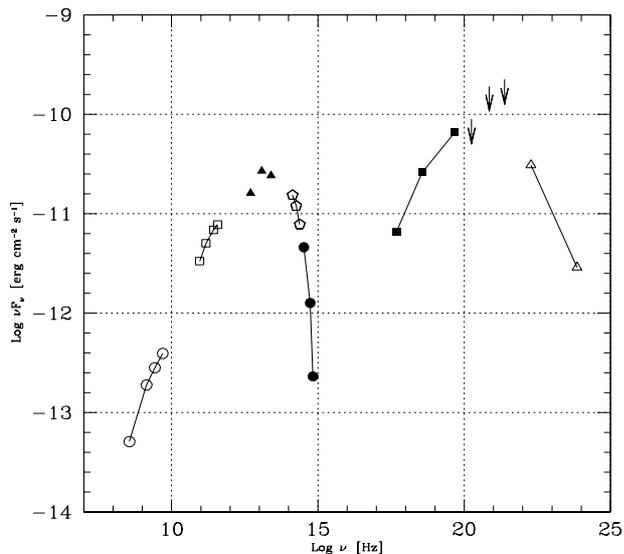


Fig. 3. The observed SED of 3C 111. We shown here all published data. Open circles are radio measurements, open squares are millimeter measurements, filled triangles are IRAS data, open pentagons are 2MASS measurements (bands *J*, *H*, *K*), filled circles are optical measurements (bands *I*, *V*, *B*), filled squares are our BeppoSAX measurements, open triangles are EGRET measurements and arrows are 2σ COMPTEL upper limits (0.75–1 MeV, 1–3 MeV, 3–10 MeV).

SED. While the correction in X-ray is easily provided by the estimate of the column density, the extinction in optical is more complex to evaluate. The visual extinction map provided by Ungerer et co-workers (1985) over an area of $1.4^\circ \times 1.2^\circ$ reveals the existence of a large condensation with small clumps of high visual extinction; however the part of the cloud just in front of 3C 111 is not the densest and therefore in this direction the extinction is moderate, A_V being only 1.3 mag. Correcting both optical/near-infrared and the X-ray band for the appropriate estimated extinction/absorption we obtain Fig. 4. The main effect of this procedure is to reduce substantially the depth of the minimum at $\nu \approx 10^{15}$ Hz. Even after this correction, the two broad peaks seen in Fig. 4 are still present and by analogy with blazars, can be attributed to non thermal synchrotron emission and to inverse Compton scattering of softer photons. Furthermore the X/gamma radiation completely dominates the radiative output: the SED of 3C 111 thus intriguingly resembles those of Compton dominated blazars. These general features are quite easily explained in the layer-spine scenario of Ghisellini et al. (2004).

6. Probability of association

The error box of 3EG J0416+3650 does not contain any obvious galactic counterparts. The variability of the EGRET source excludes a pulsar as a potential candidate as well as a supernova remnants (SN). Pulsar Wind Nebulae can be strong and variable gamma-ray emitters (Nolan et al. 2003), but using the HEASARC database we found none inside the EGRET error box; furthermore PWN are expected to be both radio and X-ray emitting objects (Roberts et al. 2002) while none of the objects we found within the 99.9% contours is both a radio and

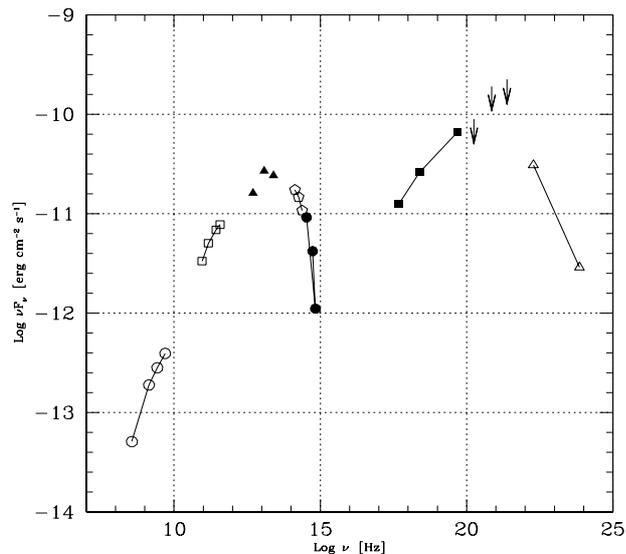


Fig. 4. The corrected SED of 3C 111. Optical and far-infrared data points (filled circles and open pentagons, respectively) have been dereddened with $A_V = 1.3$, while the X-ray point at 2 keV has been corrected for $N_H = 1.2 \times 10^{22} \text{ cm}^{-2}$.

an X-ray source except for 3C 111. We are therefore left with the possibility of an association with a galactic object such as a microquasars or a Wolf Rayet star, but also in this case no object of this type has been found inside the EGRET error box (HEASARC).

Bearing this in mind, the only other possible counterpart is an extragalactic object, with characteristics similar to those observed in blazars. 3C 111 is fully compatible with this scenario. In the light of our findings we can reevaluate the a posteriori probability of association following Mattox et al. (1997, 2001). The factors that we used for this calculation are the radio flux (6.637 Jy) and the spectral index (-0.3) of 3C 111, the 95% error radius of the EGRET source ($0^\circ:66$), the distance of 3C 111 from the center of the EGRET error box ($1^\circ:27$) and the mean distance between radio sources that are at least as strong and at least as flat as 3C 111 ($\sim 43^\circ$). The value obtained (~ 0.05 or $\sim 5\%$) is not high enough to consider the association highly probable because of the location of 3C 111 at the border of the EGRET error box. However, the location outside the 99% γ -ray probability contour (but inside the 99.9% one) should not be taken as a strong element to exclude 3C 111 as a possible counterpart of the EGRET source. As pointed out by Thompson et al. (1995) and Hartman et al. (1999), the position uncertainty region provided in the EGRET catalogues are statistical only: a “generous” allowance for an additional systematic position error due to inaccuracies in the Galactic diffuse radiation model and potential source confusion is recommended to the user, particularly for those EGRET sources located along the galactic plane. Therefore it is clearly worth searching for counterparts even outside the 99% error box.

7. Conclusions

From analysis of archived radio, millimeter, infrared, optical and X/gamma-ray data, we conclude that 3EG J0416+3650 is

likely to be associated with the radio galaxy 3C 111; furthermore we show that this source can be interpreted as a mis-oriented blazar, mainly suggested on the basis of its SED and multiwavelength characteristics. Bearing this in mind, 3C 111 could be the third radio galaxy detected by EGRET, after Centaurus A and possibly NGC 6251. This association strongly supports the scenario that radio galaxies, not only blazars, can be high energy γ -ray emitters, as suggested by Ghisellini et al. (2004). This could have important consequences in opening the search for counterparts to a more populated class of objects and in providing a new perspective in the relation between blazars and radio galaxies.

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