A likely AGN counterpart to the unidentified gamma-ray source 2FGL J0221.4+6257c

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Abstract. We report about the finding of two peculiar radio sources inside the 95% confidence ellipse of the the gamma-ray source 2FGL J0221.4+6257c detected by the *Fermi* Large Area Telescope. Both of them look particularly interesting since their morphologies, and the existence of point-like infrared counterparts, strongly point to active galactic nuclei with highly beamed relativistic jets. A blazar, or a flat spectrum radio quasar nature is tentatively proposed for the brightest one based on the extreme brightness contrast of its jet and counterjet. The possibility that this object is where the gamma-ray photons originate deserves serious consideration.
Key words: Gamma rays: stars – Radio continuum: stars – Pulsars – Active Galactic Nucleus: blazars

Introduction

The identification of gamma-ray sources without counterparts at lower-energy bands of the electromagnetic spectrum is often a difficult task due to their large position uncertainty ($\sim$0°.1-0°.2). The situation is even worse in the vicinity of the Galactic plane since this is a very obscured and crowded region, specially at optical and near infrared wavelengths. Currently, the largest available gamma-ray source catalogue is the one provided by the *Fermi* Large Area Telescope (LAT) in the 100 MeV-100 GeV energy range after its first two years of operation [Nolan et al. 2012]. However, more than 30% of its contents remain still without a known lower-energy counterpart despite years of research. Looking for them may provide very rewarding findings, such as new examples of interesting astrophysical objects (e.g. gamma-ray binaries, pulsar wind nebulae, microquasars, supernova remnants ...).

In this context, the unidentified *Fermi* LAT source 2FGL J0221.4+6257c initially attracted our attention as a possible gamma-ray binary candidate [Martí et al. 2013]. Only a handful of this selected class of binary stars is know at present. They consist of a compact object (black hole or neutron star) orbiting a luminous early-type companion, and most of the system luminosity is radiated in the gamma-ray domain. X-ray and radio emission of non-thermal nature are additional fingerprints exhibited by these remarkable objects. Our suspicion about 2FGL J0221.4+6257c came from a search in different catalogues and databases. This revealed that the emission-line, early-type star VES 737 [Coyne & MacConnell, 1983] was inside the *Fermi* LAT 95% confidence ellipse. In addition, VES 737 (V = 11.86 mag, spectral type B9V) appeared consistent with the location of the X-ray source 2E 0216.9+6248 detected during pointed observations by the Imaging Proportional Counter aboard the *EINSTEIN* (*HEAO 2*) satellite, in orbit between November 1978 and April 1981 [Harris et al. 1994]. Years later, in 2005 archival data, no X-ray emission was obvious in the only XMM-*Newton* pointing available with improved sensitivity with respect to *EINSTEIN*, thus suggesting possible X-ray variability not uncommon for a binary system.

To confirm the possible nature of 2FGL J0221.4+6257c we carried out a radio interferometric observation aimed to search for a non-thermal radio counterpart. As a result, the gamma-ray binary nature of VES 737 has not been confirmed so far. However, our observations do reveal other interesting radio sources whose positions are consistent with the *Fermi*-LAT ellipse. Two of them in particular appeared as plausible alternative counterparts to this gamma-ray source. In the following sections, we present the results of our observations and discuss the available evidence about the possible nature of 2FGL J0221.4+6257c.

Radio observations

The field of 2FGL J0221.4+6257c was observed with the Karl G. Jansky Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO) of the USA. The observation was carried out on 17th June 2011, between 12^h-13^h UTC, with an on-source integration time of about 40 minutes. The array was in its most extended A-configuration. The L-Band (20 cm) receivers were used for which the new WIDAR correlator was available at that time. This provided an excellent performance of the array as compared with the old VLA settings. Visibility data were acquired in spectral-line mode, with two spectral windows of 128 MHz wide divided into 64 channels each (total bandwidth 256 MHz). The VLA was pointed to the VES 737 position. Nevertheless, at 20 cm the antennae primary beam is wide enough to map the full *Fermi* LAT 95% confidence ellipse. Data were calibrated and processed using the new software package CASA version 4.1.0. The amplitude and bandpass calibration was tied to 3C48, while J0228+6721 was used for phase calibration. Maps were computed using the CASA clean task and a few iterations of self calibration were conducted as well.

The resulting map is presented as contour plots in the different panels of Fig. 1. No radio source is detected at the VES 737 position, but a dozen of other radio sources are clearly detected within the boundaries of the *Fermi*-LAT 95% confidence ellipse. Their positions and 20 cm flux densities are given in Table 1. The most peculiar ones (Id. #s 6, 11 and 12) are shown in more detail in the zoomed insets of the figure, and we will address them in the following section.

Discussion

Radio observations of gamma-ray sources have provided in the past a good approach towards their identification. Indeed, radio emission of non-thermal nature is often a good tracer of the relativistic particles responsible for the high-energy photons. A radio counterpart to the early type star VES 737 has not been detected. The 20 cm flux density upper limit corresponds to 93 μJy (three times the rms noise).

Although orbital variability could be invoked, this negative result casts doubts on the gamma-ray hypothesis that originally drove our work. Thus, other physical scenarios need to be explored.

The *Fermi* catalogue tentatively associates 2FGL J0221.4+6257c with the supernova remnant (SNR) G132.7+01.3, also known as G132.4+02.2, for which a 2.2 kpc distance has been proposed [Green 2009]. However, this SNR has a very large angular size ($80'$) and the association could be a simple line of sight effect. The nearby pulsar PSR J0215+6218 [Lorimer et al. 1998] was discovered towards a direction overlapping with the remnant. It could be physically related to it, but its position is clearly too far from the *Fermi*-LAT source.

A close inspection of the Fig. 1 map reveals a couple of interesting objects that deserve follow up attention. One of them is composed by radio sources #11 and #12, which are connected by extended emission detected at a very marginal level (see lower-left inset of the figure). This morphology immediately opens the possibility of an extragalactic jet source from an Active Galactic Nucleus (AGN). The other object is the one labelled as #6. It actually consists of two close components (6a and 6b, as listed in Table 1). With an angular separation of about $7\overset{''}{.}5$ (see lower-right inset), source 6a appears to contain a compact core while source 6b is clearly extended in nature.

Although the morphology of source #6 could correspond to another extragalactic jet source with a one-sided jet, the overall appearance of its two components is also reminiscent of a Pulsar Wind Nebula (PWN) created by the magnetosphere of a high-velocity pulsar. Possibly the best known example of this kind of PWNe is G359.23−0.82, also nicknamed as the Mouse [Hales et al. 2009], where compact radio emission from the pulsar is heading a sort of cometary tail behind it.

Table 1. Radio sources inside the 95% confidence ellipse of 2FGL J0221.4+6257c

Source #	$\alpha_{\rm J2000.0}$	$\delta_{\rm J2000.0}$	$S_{\rm 20\ cm}^{\rm peak}$(mJy)	$S_{\rm 20\ cm}^{\rm total}$(mJy)	Notes
1	$02^h20^m39\overset{s}{.}30 \pm 0\overset{s}{.}02$	$+62°56'19\overset{''}{.}7 \pm 0\overset{''}{.}1$	0.32 ± 0.05	0.32 ± 0.05	–
2	$02^h20^m51\overset{s}{.}914 \pm 0\overset{s}{.}003$	$+63°01'10\overset{''}{.}30 \pm 0\overset{''}{.}02$	1.79 ± 0.05	1.91 ± 0.09	–
3	$02^h21^m05\overset{s}{.}42 \pm 0\overset{s}{.}01$	$+63°01'42\overset{''}{.}4 \pm 0\overset{''}{.}1$	0.50 ± 0.05	0.6 ± 0.1	–
4	$02^h21^m07\overset{s}{.}62 \pm 0\overset{s}{.}01$	$+62°58'40\overset{''}{.}1 \pm 0\overset{''}{.}1$	0.48 ± 0.05	0.5 ± 0.1	–
5	$02^h21^m12\overset{s}{.}27 \pm 0\overset{s}{.}02$	$+62°55'38\overset{''}{.}1 \pm 0\overset{''}{.}1$	0.39 ± 0.05	0.5 ± 0.1	–
6(a)	$02^h21^m24\overset{s}{.}96 \pm 0\overset{s}{.}02$	$+62°56'30\overset{''}{.}5 \pm 0\overset{''}{.}1$	0.22 ± 0.03	0.46 ± 0.09	Core
6(b)	$02^h21^m25\overset{s}{.}02 \pm 0\overset{s}{.}02$	$+62°56'38\overset{''}{.}1 \pm 0\overset{''}{.}2$	0.17 ± 0.03	0.9 ± 0.1	Radio lobe
7	$02^h21^m35\overset{s}{.}929 \pm 0\overset{s}{.}004$	$+63°01'14\overset{''}{.}06 \pm 0\overset{''}{.}03$	1.39 ± 0.05	1.47 ± 0.09	–
8	$02^h21^m36\overset{s}{.}31 \pm 0\overset{s}{.}03$	$+62°52'30\overset{''}{.}0 \pm 0\overset{''}{.}2$	0.26 ± 0.05	0.5 ± 0.1	–
9	$02^h21^m40\overset{s}{.}40 \pm 0\overset{s}{.}01$	$+62°52'00\overset{''}{.}0 \pm 0\overset{''}{.}1$	0.47 ± 0.05	0.47 ± 0.09	–
10	$02^h21^m45\overset{s}{.}32 \pm 0\overset{s}{.}01$	$+62°54'20\overset{''}{.}1 \pm 0\overset{''}{.}1$	0.44 ± 0.05	0.5 ± 0.1	–
11	$02^h22^m12\overset{s}{.}513 \pm 0\overset{s}{.}002$	$+62°58'37\overset{''}{.}41 \pm 0\overset{''}{.}01$	3.19 ± 0.05	3.3 ± 0.1	Core
12	$02^h22^m14\overset{s}{.}012 \pm 0\overset{s}{.}001$	$+62°59'04\overset{''}{.}00 \pm 0\overset{''}{.}01$	7.00 ± 0.05	10.1 ± 0.1	Radio lobe

The contour map of source # 6 in Fig. 1 is not sufficiently good to distinguish between a beamed AGN and a cometary-like PWN. Typical gamma-ray luminosities of *Fermi* pulsars are distributed in the range 10^{33}-10^{35} erg s^{-1} [Abdo et al. 2010]. The 2FGL J0221.4+6257c energy flux in the *Fermi* catalogue is $(2.1 \pm 0.3) \times 10^{-11}$ erg cm^{-2} s^{-1} based in a LogParabola spectral fit in the 0.1-100 GeV energy band. This translates into a gamma-ray luminosity $L_{0.1-100\ \rm GeV} = (2.6 \pm 0.4) \times 10^{33}$ erg s$^{-1}[d/\rm kpc]^2$, where d is the distance at present unknown to us. It could be easily accounted for by a pulsar within a few kpc from us. However, no radio pulsations down to ~ 1 mJy were detected at its position when the SNR G132.7+01.3 was searched for pulsars [Lorimer et al. 1998].

Table 2. GLIMPSE counterparts to peculiar radio sources in the 2FGL J0221.4+6257c field

SSTGLMC source name	$\alpha_{\rm J2000.0}$	$\delta_{\rm J2000.0}$	3.6 μm magnitude	4.8μm magnitude	Radio association
G133.0327+01.8993	$02^h22^m12\overset{s}{.}61$	$+62^\circ58'37\overset{''}{.}7$	13.44 ± 0.04	12.71 ± 0.03	#11
G132.9600+01.8351	$02^h21^m25\overset{s}{.}00$	$+62^\circ56'30\overset{''}{.}1$	16.7 ± 0.1	16.4 ± 0.1	#6a

In an attempt to better discriminate between different interpretations, we examined the far infrared images of the Galactic Legacy Infrared Mid-Plane Survey Extraordinaire (GLIMPSE) obtained by the *Spitzer* Space Telescope (SST) [Benjamin et al. 2003, Churchwell et al. 2009]. This wavelength domain is also helpful to minimize the severe effects of interstellar absorption in the Galactic plane, that render optical observations almost useless. This survey interestingly shows that two GLIMPSE point-like objects are almost in perfect coincidence with the peaks of radio sources #11 and #6a (see Table 2). They are detected in the 3.6 and 4.8 μm bands. The GLIMPSE coordinates are accurate to $\pm 0\overset{''}{.}3$ in both axes and the matches with the radio positions of Table 1 are excellent within 1 to 2σ.

The existence of infrared point-like objects as very likely counterparts to the VLA sources #11 and #6a is naturally expected if the AGN scenario is correct. The compact nucleus of an active galaxy is often so bright that it outshines the galaxy itself. On the other hand, the optical/infrared counterparts of pulsars are often extremely faint sources often within reach of 10-m class telescopes only. In this context, we believe that the VLA sources #11 and #6a can be considered, with high probability, as AGNs from which collimated jets emanate. The radio jet lobes powered by these jets would then correspond to radio sources #12 and #6b, respectively. The clear absence of a counterjet in the VLA maps of Fig. 1 indicates a significant value for the jet to counterjet brightness ratio: $R \geq 109$ and $R \geq 10$, respectively. At least in the first case, the derived ratio is high enough so that beaming due to relativistic effects requires a jet ejection angle θ approaching the line of sight. Based on the two VLA spectral windows acquired (0.4 GHz apart), the spectral index of source #12 is about $\alpha \simeq -1.0$, while the AGN core (source #11) has an almost flat radio spectrum ($\alpha \simeq 0$). According to the Doppler boosting formula:

$$R = \left(\frac{1 + \beta \cos\theta}{1 - \beta \cos\theta}\right)^{k-\alpha}, \qquad (1)$$

where β is the jet velocity in units of the speed of light. When this equation is applied to source #12 assuming a continuous jet ($k = 2$), the jet ejection angle from source #11 has to be $\theta \leq 49^\circ$.

Therefore, we propose that the VLA source #11 can be most likely interpreted as a blazar, or a flat spectrum radio quasar (FSRQ), seen through the Galactic plane, and we consider it as our primary counterpart candidate to 2FGL J0221.4+6257c. Further observational work is currently going on to confirm the proposed identification.

Conclusion

We have presented deep radio observations of the unidentified gamma-ray source 2FGL J0221.4+6257c, at the 20 cm wavelength, obtained with subarcsecond angular resolution, and with a rms sensitivity of 31 μJy. A radio counterpart to the early-type star VES 737 that was initially suspected to be a possible gamma-ray binary has not been detected. This negative result prompted us to carefully examine the radio source contents of the *Fermi*-LAT 95% confidence ellipse and locate other possible radio counterpart candidates.

Two radio sources, that we propose to be of AGN nature, have been identified in the direction of 2FGL J0221.4+6257c. Their compact radio cores are both remarkably consistent with point-like GLIMPSE infrared sources, thus reinforcing the AGN interpretation. Moreover, the brightest of these radio sources (#11 in our data) displays a large value of its jet to counterjet flux density ratio. This fact strongly indicates that we are dealing with a blazar, o perhaps a FSRQ. Both kinds of AGNs are well known gamma-ray emitters and, therefore, we suggest that this extragalactic jet source is the most likely counterpart candidate to the 2FGL J0221.4+6257c. We expect that future observational work in progress will confirm this identification.

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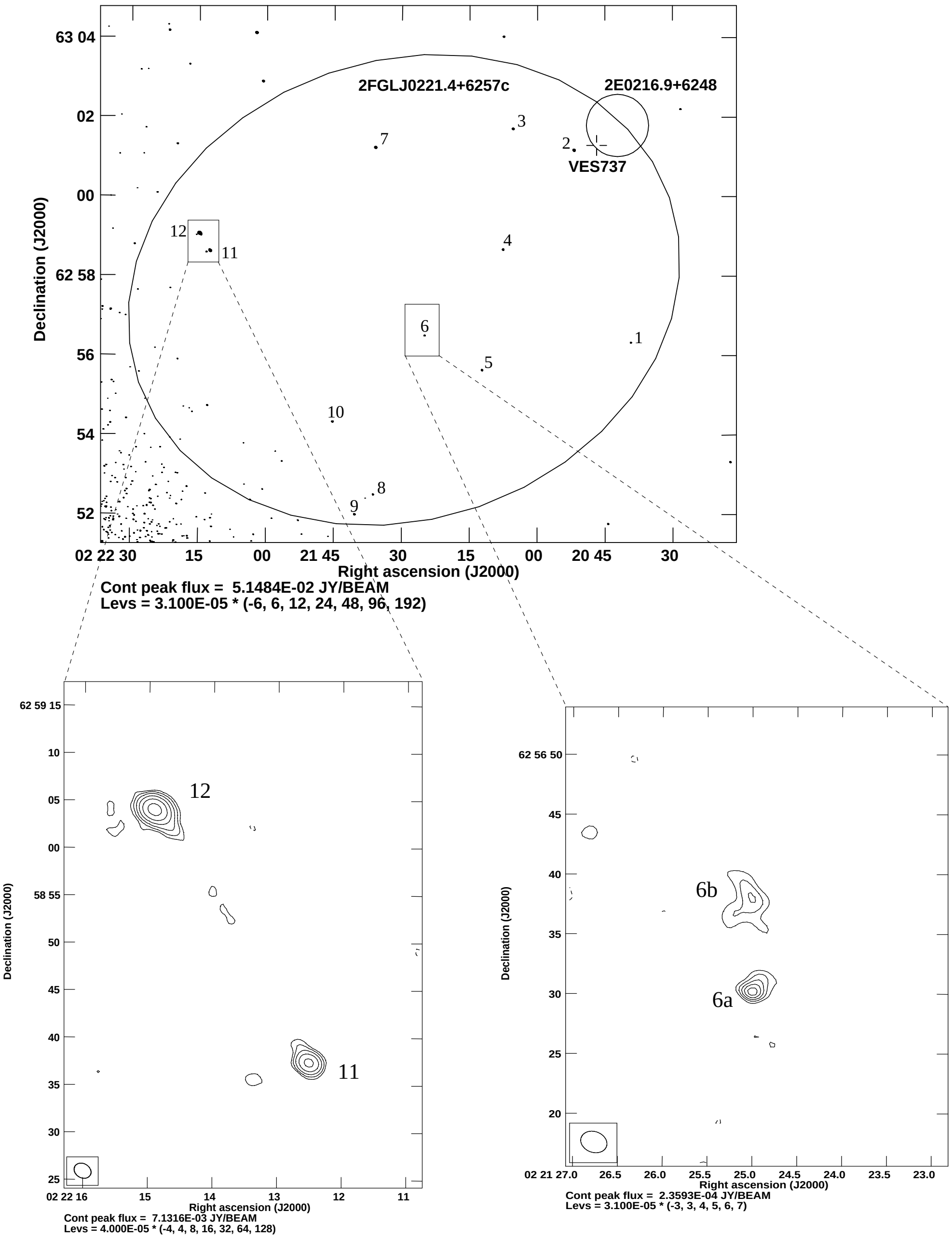

Fig. 1. Top. Wide-field contour radio map of the 2FGL J0221.4+6257c region obtained with the Jansky VLA at the 20 cm wavelength. The large ellipse represents the 95% confidence location of the *Fermi* gamma-ray source. The small circle indicates the positional error of an EINSTEIN X-ray source in the same field, while the cross with a gap corresponds to the location of the emission-line star VES 737 where no radio emission was detected. Radio sources detected inside the *Fermi* ellipse are numbered from 1 to 12 in right ascension order. The rms noise in the central parts of the map amounts to 31 μJy. **Bottom.** Zoomed contour plots of the two most relevant radio sources detected towards 2FGL J0221.4+6257c and discussed in the text. Both of them are likely of AGN nature and #11 possibly of blazar/FSRQ type. The ellipses at the bottom left corner show the synthesized beam of the interferometer corresponding to $1''.87 \times 1''.50$, with position angle of $60^\circ.5$.