An inquiry into the nature of the gamma-ray source 3EG J1828+0142

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Abstract. The unidentified, low-latitude, γ-ray source 3EG J1828+0142 presents high levels of variability and a steep spectral index $\Gamma \sim 2.7$. Here we propose a model for this source where the high-energy emission is produced by a galactic Kerr-Newman black hole. The model takes into account electron-positron annihilation losses in the calculation of the expected spectral energy distribution and can reproduce the observational features, including the absence of a strong radio counterpart. We also report the discovery of a nearby supernova remnant that could be associated with the original supernova explosion that created the black hole. Several faint radio sources were also detected in the radio field within the inner γ-ray confidence contour and their spectral index estimated. Some of these sources could be the expected weak radio counterpart.

Key words: gamma rays: theory – gamma rays: observations – radio continuum: ISM – ISM: supernova remnants – black hole physics

1. Introduction

During its lifetime, the EGRET instrument on board the Compton Gamma Ray Observatory detected 170 gamma-ray point sources which are not clearly identified with known objects at lower frequencies (Hartman et al. 1999). About half of these sources are concentrated near the galactic plane, suggesting that they have a relatively local origin (Romero et al. 1999a; Gehrels et al. 2000).

Different possible counterparts have been suggested for the galactic population of gamma-ray sources: supernova remnants (SNRs) in interaction with molecular or atomic clouds (e.g. Sturner & Dermer 1995; Esposito et al. 1996; Combi et al. 1998), massive stars with strong stellar winds (e.g. Romero et al. 1999a), young pulsars (e.g. Yadigaroglu & Romani 1997; Zhang et al. 2000), and isolated black holes (e.g. Dermer 1997; Punsly 1998a,b).

Recent variability analysis of the data in the Third EGRET catalog by Torres et al. (2000) show that many of the sources

at low galactic latitudes display high levels of variability, confirming the results found by McLaughlin et al. (1996) for the sources contained in the Second EGRET catalog. The conjunction of steep gamma-ray spectral indices and strong variability in a few sources seems to suggest the existence of an entirely new population of high-energy sources in the Galaxy. One such source is 3EG J1828+0142, located at $(l, \ b) \approx (31.9°, \ 5.78°)$. Hartman et al. (1999) suggest that it could be an Active Galactic Nucleus (AGN), although there is no strong radio blazar within the 95% confidence contour. The source presents a steep spectral index with a value $\Gamma = 2.76 \pm 0.39$ and variable gamma emission. If we introduce the variability index $I = \mu_{\rm s} / \langle \mu \rangle_{\rm p}$, where $\mu_{\rm s} = \sigma / \langle F \rangle$ is the fluctuation index of the gamma-ray source and $\langle \mu \rangle_{\rm p}$ is the averaged fluctuation index of all known gamma-ray pulsars (which are usually considered as a non-variable population), we found that $I = 5.5$, a clear indication of strong variability.

In this paper, we propose that this source could be a magnetized black hole which originated from a relatively recent supernova explosion. We have used background filtering techniques to isolate the radio image of an extended SNR (which overlaps the gamma-ray signal) from the contaminating diffuse emission of the Galaxy, in radio observations at two frequencies. Both the variability and the steep spectral index of the gamma-ray radiation argue against the possibility that the compact object left after the explosion is a pulsar. We present a model for a magnetized black hole that can reproduce the observed high-energy spectrum and which predicts an intense electron-positron annihilation line that could be detected later by the SPI spectrometer or the IBIS imager of the INTEGRAL satellite.

In the next section we describe the data analysis technique. Then, we present our results, briefly discuss the probability of a chance association of the SNR and the gamma ray source, and outline the black hole model. Finally, we discuss the predictions that can test our proposal.

2. Data analysis and results

We have studied the surroundings of 3EG J1828+0142 using radio data from the surveys by Haslam et al. (1981) and Reich & Reich (1986). The background filtering method developed by Sofue & Reich (1979) was applied to remove the diffuse

Table 1. Measured properties of the SNR

Property	Value
Galactic coordinates (center)	$(+32.6°, 7.3°)$
Angular size (deg $\times$ deg)	4.0×4.0
Flux density (408 MHz)	44.7 ± 6.5 Jy
Flux density (1420 MHz)	18.2 ± 2.1 Jy
Average spectral index	0.72 ± 0.18
Distance (pc)	~ 940

galactic emission that hides weak and extended radio structures at low galactic latitudes. The procedure and its application to find low surface brightness SNRs is described in detail by Combi et al. (1998, 1999). In the present case we have applied a gaussian filtering beam of $90' \times 90'$ to 0.408- and 1.42-GHz maps of a $7° \times 7°$ field around 3EG J1828+0142, identifying a previously unnoticed shell-type structure centered at $(l, b) \approx (32.6°, 7.3°)$. It is a large $(4° \times 4°)$ source with a total flux density at 1.42 GHz of 18.2 ± 2.1 Jy and a nonthermal spectral index $\alpha = 0.72 \pm 0.18$ $(S(\nu) \propto \nu^{-\alpha})$, very similar to other shell-type SNRs (see Green 1998). In Fig. 1, upper panel, we show the filtered 1.42-GHz image of the source. The large continuum sources at the South of the new remnant candidate are probably related to the North Polar Spur (see Jonas's 1999 large-scale map of the region at 2.326 GHz). Table 1 lists the main characteristics of the new SNR candidate. The distance of ~ 940 pc has been estimated using the $\Sigma - D$ relationship derived by Allakhverdiyev et al. (1986) for low surface brightness SNRs, and it should be considered a very rough estimate. The large apparent size of the remnant suggests that it is located nearby.

If we assume a standard energy release of $\sim 0.4 \times 10^{51}$ erg for the supernova explosion and a typical intercloud density of 0.1 cm^{-3} for the interstellar medium (Spitzer 1998), we get from the Sedov solutions that the age of the remnant is $\sim 43\,500$ yr. A transverse velocity of ~ 730 km s^{-1} is then required for the compact object left by the explosion to be currently located near the outer boundary of the SNR. A denser ambient medium would imply, of course, smaller velocities. For instance, with a density ~ 1 cm^{-3} we get a more reasonable velocity of ~ 240 km s^{-1}. It should be also taken into account that the determination of the distance has an uncertainty of $\sim 50\%$, so even lower velocities are possible. Lyne & Lorimer (1994) have recently estimated that the space velocity of pulsars at birth has a mean value of 450 ± 90 km s^{-1}, which is a factor three higher than earlier estimates (e.g. Lyne et al. 1982). Stellar black holes should present a velocity distribution similar to that of pulsars.

In order to explore the small-scale radio emission within the inner probability contours of the gamma-ray source we have used the NVSS Sky Survey with an angular resolution of 45 arcseconds (Condon et al. 1998). There are just four point sources with fluxes above 10 mJy within the 65% probability contour of 3EG J1828+0142. They have been labeled from S1 to S4 in Fig. 1, lower panel. All these sources are nonthermal, with flux densities of between ~ 5 and 100 mJy at 1.4 GHz. Sources
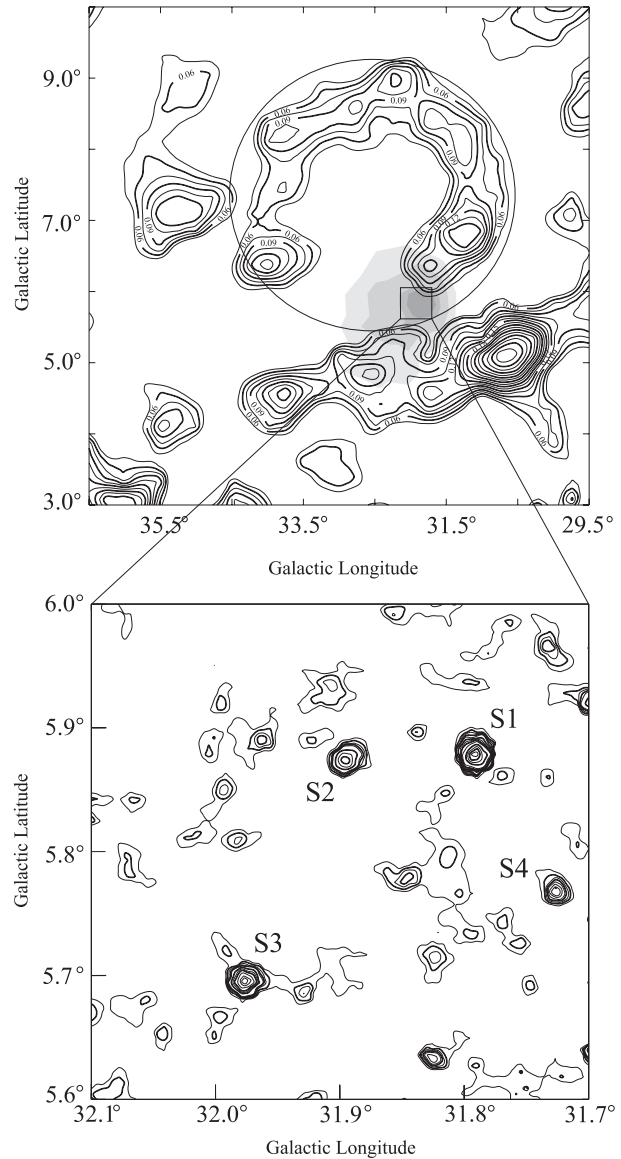
Fig. 1. Upper panel: Filtered large-scale radio emission around the γ-ray source 3EG J1828+0142 at 1.4 GHz. Radio contours are shown in steps of 0.015 K, starting from 0.045 K (noise level is 0.02 K). The γ-ray probability contours are superposed in gray scale. Lower panel: Small-scale 1.42-GHz emission obtained from the VLA sky survey for the region within the inner probability contour of the γ-ray source. Radio contours are in steps of 1 mJy beam^{-1}, starting from 1 mJy beam^{-1}. The characteristics of the four point sources labeled from S1 to S4 are detailed in Table 2.

S1, S2 and S4 do not present a resolved structure, whereas the source S3 has two weak extensions towards the Northeast and Southwest. It is hard to say, however, whether these features are artifacts due to confusion with weak, neighboring sources, or real components of S3. The characteristics of the four sources are summarized in Table 2. The sources S2, S3 and S4 have no entry in any point source catalog at present. We have estimated lower limits to their radio spectral index using the 5 GHz survey by Condon et al. (1994), which is sensitive down to 5 mJy.

Table 2. Characteristics of the point radio sources inside the γ-ray contour

Source	(l, b) (deg, deg)	$F_{1.4\mathrm{GHz}}$ (mJy)	$F_{365\mathrm{MHz}}$ (mJy)	α	ID
S1	(31.79,+5.87)	78.4	275.4	0.9	TXS 1825+016[1]
S2	(31.89,+5.88)	13.8	–	> 0.8	–
S3	(31.98,+5.69)	25.1	–	> 1.2	–
S4	(31.73,+5.77)	7.3	–	> 0.3	–

[1] Douglas et al. (1996)

3. Probability of chance association

In order to make quantitative estimates of the probability of a pure chance superposition between the SNR and the gamma-ray source we have adopted the numerical code developed by Romero et al. (1999b) and used by Romero et al. (1999a) to study the positional association of unidentified EGRET sources with various populations of galactic objects. The code calculates angular distances between different kinds of celestial objects contained in selected catalogues, and establishes the level of positional correlation between them. Numerical simulations using large numbers of synthetic populations are then performed in order to determine the probabilities of purely chance associations. When generating synthetic populations of γ-ray sources the distribution in galactic latitude is constrained to be the same as the one actually observed for the 3EG sources. This is necessary in order to obtain reliable results since the distribution of the 3EG sources is non-isotropic, with a strong concentration towards the galactic plane. The reader is referred to the paper by Romero et al. (1999a) for further details of the simulation code.

Our results for 3EG J1828+0142 indicate that the probability of finding by chance a gamma-ray source with its 95% confidence contour within the outer boundary of the SNR is 7.0×10^{-2}. The probability of finding a variable gamma-ray source (estimated taking into account the actual fraction of variable sources in the 3EG catalog according to Torres et al. 2000) is lower: 1.0×10^{-2}. These values are not too compelling, but if we calculate the probability of the gamma-ray source being a background AGN seen through the galactic plane and associated by chance with the SNR, we get a value of $\sim 4 \times 10^{-6}$, which is significantly lower. In making this calculation we have extrapolated the isotropic population of already detected gamma-ray emitting AGNs towards the region obscured by the galactic disk emission, performing simulations with no gamma-ray source density gradient towards the plane.

4. Magnetized black hole model

Kerr-Newman isolated black holes are interesting candidates for the production of variable gamma-ray sources in the Galaxy (Punsly 1998a, 1998b). The configuration of a simple axisymmetric magnetosphere around a maximally rotating black hole attains a minimum energy configuration when the hole and the magnetosphere have equal and opposite charge. Punsly (1998a) has shown that the magnetospheric charge can be supported in a stationary orbiting ring or disk. The entire magnetized system is stable only in an isolated environment, otherwise accretion into the black hole would disrupt the ring and its fields. Kerr-Newman black holes are charged similarly to neutron stars in pulsars. However, unlike neutron stars, black holes have no solid surface and consequently no thermal X-ray emission is expected. These objects can support strong magnetized bipolar winds in the form of jets, where gamma-ray emission is originated by the inverse Compton mechanism (Punsly 1998a). Since both magnetic and rotation axes are always aligned therein, their emission is nonpulsating (NP) and for such a reason they have been called NP black holes (Punsly 1999).

We propose that 3EG J1828+0142 could be a NP black hole created by the same supernova explosion that produced the nearby SNR. In the following, we present a specific model that reproduces the steep gamma-ray spectrum observed at EGRET energies. The model takes into account electron-positron annihilations in the inner jet, self-Compton cooling of the relativistic leptons, and synchrotron emission of the outer jet, in such a way that it provides concrete predictions for different wavebands that can be tested in the near future.

We shall follow the treatment given by Punsly (1998a), considering a black hole of mass $M = 4\,M_\odot$ and a polar magnetic field strength $B = 10^{11}$ G. The inner jet begins at the inner light cylinder (located at a cylindrical radius r_{lc} from the symmetry axis):

$$r_0 = r_{\mathrm{lc}} = 8 \times 10^7 \quad \mathrm{cm}; \tag{1}$$

this is at a distance R_0 from the event horizon:

$$R_0 = 10^8 \quad \mathrm{cm}. \tag{2}$$

The radius of the jet r is given in terms of the axial displacement from the black hole, R, as:

$$r = (R/R_0)^\epsilon\, r_0, \quad \epsilon = 0.2. \tag{3}$$

Thus, the inner jet is tightly collimated. Its length is given by:

$$R_{\mathrm{max}} = 1.5 \times 10^{12} \quad \mathrm{cm}. \tag{4}$$

The Doppler enhancement factor is constant and assumed to be:

$$\delta = 2.5. \tag{5}$$

The magnetic field and the particle number density vary with R as:

$$B = 100\,(R/R_0)^{-\epsilon} \quad \mathrm{G} \tag{6}$$

and

$$N = N_\Gamma \, (R/R_0)^{-\epsilon}, \tag{7}$$

where

$$N_\Gamma = 7.5 \times 10^{13} \quad \text{cm}^{-3}, \tag{8}$$

$$n = \int_{\gamma_{\min}}^{\gamma_{\max}} N_\Gamma \gamma_{\text{th}}^{-\Gamma} \, d\gamma_{\text{th}} \,, \tag{9}$$

$$\Gamma = 2. \tag{10}$$

The maximum thermal Lorentz factor, $\gamma_{\text{th}} = \gamma_{\max}$, is:

$$\gamma_{\max} = 1.5 \times 10^4 \, (R/R_0)^{-0.225}. \tag{11}$$

Gamma-rays are produced in this inner jet by electron-positron annihilations and self-Compton emission. The annihilation luminosity is enhanced by Doppler boosting in the jet as:

$$L_{\text{obs}}^{\text{ann}} = \delta^3 L_0^{\text{ann}}, \tag{12}$$

where

$$L_0^{\text{ann}} = (3/32)\sigma_T c(\Gamma - 1)^2 n^2 m_e c^2 V \times$$
$$\left[\frac{2}{(\Gamma - 1/2)(\Gamma + 1/2)} + \frac{2(2\Gamma - 1)}{\Gamma^2(\Gamma - 1)^2} \right] \tag{13}$$

(see Roland & Hermsen 1995, noticing the wrong exponent in their Eq. 4, where it should be no dependency on α). In the above Eq. (13), n is the number density of electron-positron pairs, V is the volume where the annihilations occur, and σ_T is the Thomson cross section. The peak of the annihilation line will be at an energy:

$$E_{\max} = \delta \gamma_{\min} 0.511 \text{ MeV}, \tag{14}$$

which in our model corresponds to 6.4 MeV, assuming $\gamma_{\min} \approx$ 5. The spectral shape of the annihilation line is as in Böttcher & Schlickeiser (1996). Notice, however, that these authors consider an external source of photons for the inverse Compton radiation and, consequently, their conclusions on the minimum leptonic number density in the jet do not apply to our case.

The outer jet, which is responsible for the bulk of the synchrotron emission, can be parameterized as a direct extrapolation of the inner jet:

$$R_0^{\text{out}} = 1.5 \times 10^{12} \quad \text{cm}, \tag{15}$$

$$r_0^{\text{out}} = 5.5 \times 10^8 \quad \text{cm}, \tag{16}$$

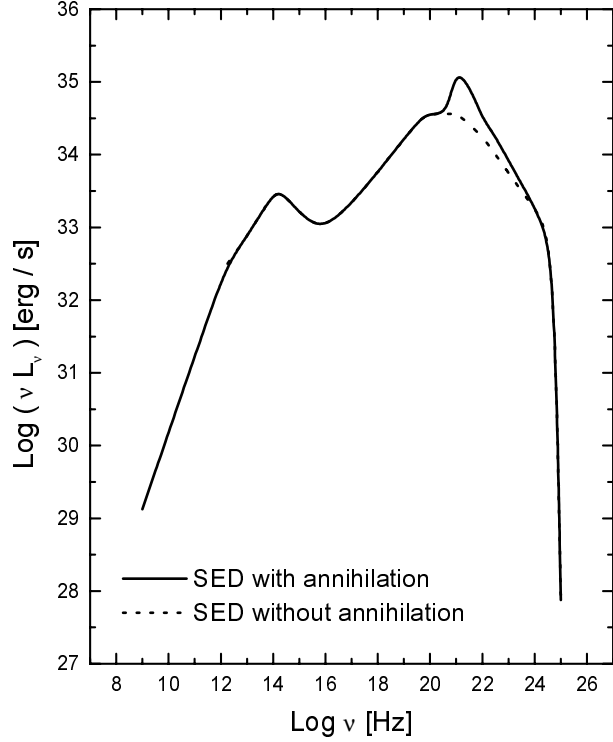$$r^{\text{out}} = (R/R_0^{\text{out}})^{1.5} \, r_0^{\text{out}}, \tag{17}$$

$$R_{\max}^{\text{out}} = 1.5 \times 10^{15} \quad \text{cm}, \tag{18}$$

$$\Gamma = 2, \quad \alpha = (\Gamma - 1)/2 = 0.5, \tag{19}$$

$$\delta = 2.5(R/R_0^{\text{out}})^{-0.1}, \tag{20}$$

$$B = 14.6 \, (R/R_0^{\text{out}})^{-1.5} \quad \text{G}, \tag{21}$$

$$N_\gamma = 1.1 \times 10^{13}(R/R_0^{\text{out}})^{-3.0} \quad \text{cm}^{-3}, \tag{22}$$

Fig. 2. Spectral energy distribution for the magnetized black hole model.

$$\gamma_{\max} = 1.72 \times 10^3(R/R_0^{\text{out}})^{-0.25}. \tag{23}$$

The bulk of the gamma-ray emission originates in the inner jet. We have computed its emissivity using the synchrotron self-Compton (SSC) formalism developed for AGNs by Ghisellini et al. (1985) and adapted to magnetized black holes by Punsly (1998b). The computed spectral energy distribution (SED) is shown in Fig. 2. Notice that the radio luminosity is low, so no strong point-like counterpart is expected at centimeter wavelengths. The radio jets and the terminal radio lobes should appear as a weak (< 30 mJy at 5 GHz) source with an angular size of a few arcseconds. Any of the sources in Table 2, then, are potential counterparts.

At a few MeV, the gamma-ray annihilation luminosity exceeds the SSC emission and the spectrum presents a broad peak. The pair annihilation contribution produces a steepening in the spectrum, which presents an index $\Gamma \sim 2.7$ in the EGRET energy band, consistent with the observations.

5. Discussion and conclusions

We have shown in the previous section that when electron-positron annihilation effects are taken into account in the bipolar magnetically dominated wind ejected by a Kerr-Newman black hole in isolation, a steep-spectrum gamma-ray source with no strong radio counterpart can be produced. The wind, which is tightly collimated into a jet, possibly experiences strong dissipation near the outer light cylinder (i.e. at $\sim 8 \times 10^7$ cm from the black hole) due to plasma instabilities and shocks. These

dissipative processes can load the jet with hot plasma. If the inner jet was to propagate with a bulk Lorentz factor of 5 and was viewed at 20 degrees off the axis, a Doppler factor of 2.5 would be attained as in Eq. (20). The jet is likely to wiggle either as a consequence of interactions with the enveloping medium or by firehose instabilities. If the jet were to wobble ± 5 degrees from its nominal value of $20°$, then the gamma-ray luminosity would vary by a factor of 9. Thus, extreme variability is expected in our model.

There are two main types of observations that could be performed in the immediate future to confirm our proposal of the nature of the source 3EG J1828+0142. VLBA observations of the sources in Table 2 could reveal some structure unresolved in the VLA images and show evidence of the twin jets and their end points in the ISM, if there is, indeed, a NP black hole which produces 3EG J1828+0142. On the other hand, observations with the gamma-ray spectrometer SPI and the imager IBIS in the forthcoming INTEGRAL mission should show evidence of the electron-positron annihilation line, which has a luminosity of $\sim 1.8 \times 10^{35}$ erg s^{-1} in the present model. The expected flux, $\sim 10^{-5}$ ph cm^{-2} s^{-1}, depends on some uncertain parameters like the width of the line and the Doppler factor. It is not surprising that COMPTEL instrument of the late Compton Gamma-Ray Observatory did not detect the source, since it would required at least two weeks of integration time and there is not yet a satisfactory model of the galactic gamma-ray background (Schönfelder et al. 2000). Notwithstanding, recent background modeling by Bloemen et al. (2000), including bremsstrahlung and inverse Compton components, shows a flux excess in the galactic disk at a few MeV that could be the effect of unidentified point sources similar to the one discussed here.

X-ray observations with the Chandra observatory also could be very useful in identifying the lower frequency counterpart of 3EG J1828+0142. The expected luminosity of the NP black hole in the Chandra energy range is $\sim 10^{34}$ erg s^{-1}, with a spectral index $\Gamma = 1.5 \pm 0.25$. It should appear as a point source positionally coincident with one of the nonthermal radio sources detected in the field.

The fact that the point-like radio sources found within the inner confidence contour of the gamma-ray source have, in most cases, a steeper spectral index than the canonical value of 0.5 expected from the outer jet can be explain by the contribution from the two lobes of radio emission formed at the points where the outer jets end, approximately 0.1 pc from the black hole. The emission from these lobes, which is not taken into account in the SED shown in Fig. 2, has been modeled by Punsly (1998b). The radio spectrum from these regions is expected to be steeper than the emission from the jet, with values of $\alpha \sim 1.15$ at 1 GHz (Punsly 1998b).

The recent variability analysis of the unidentified gamma-ray sources in the Third EGRET catalog carried out by Torres et al. (2000) shows that the most variable sources near the galactic plane tend to present steep indices $\Gamma > 2.5$. The model

presented here is capable of explaining the association of such indices with high levels of variability and the absence of strong radio counterparts in a galactic source. The discovery of a nearby SNR, also reported in this work, provides additional support for the existence of a young black hole behind the source detected by EGRET.

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