Chasing the second gamma-ray bright isolated neutron star: 3EG J1835+5918/RX J1836.2+5925

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Abstract. The EGRET telescope aboard NASA’s Compton GRO has repeatedly detected 3EG J1835+5918, a bright and steady source of high-energy gamma-ray emission with no identification suggested until recently. The long absence of any likely counterpart for a bright gamma-ray source located 25° off the Galactic plane initiated several attempts of deep observations at other wavelengths. We report on counterparts in X-rays on a basis of a 60 ksec ROSAT HRI image. In order to conclude on the plausibility of the X-ray counterparts, we reanalyzed data from EGRET at energies above 100 MeV and above 1 GeV, including data up to CGRO observation cycle 7. The gamma-ray source location represents the latest and probably the final positional assessment based on EGRET data. The X-ray counterparts were studied during follow-up optical identification campaigns, leaving only one object to be likely associated with the gamma-ray source 3EG J1835+5918. This object, RX J1836.2+5925, has the characteristics of an isolated neutron star and possibly of a radio-quiet pulsar.

1. Gamma-Ray Observations

3EG J1835+5918 was first discovered at photon energies above 100 MeV by the EGRET instrument aboard NASA’s Compton GRO during regularly scheduled observations in 1991. The source was repeatedly seen whenever it was in the field of view of the EGRET instrument. However, the first observation performed with a close on-axis pointing towards 3EG J1835+5918 using EGRET was only made in CGRO observation cycle 7 in 1998. EGRET observations performed at large off-axis viewing angle are problematic due to the degradation of the instrumental point spread function (PSF). The first report on GRO J1837+59 (Nolan et al. 1994) included only data from EGRET observations between 1991 and 1993. The source has been subsequently listed in the EGRET catalogs as GRO J1837+59 (Fichtel et al. 1994) and 2EG J1835+5919 (Thompson et al. 1995). With the appearance of the Third EGRET catalogue (E > 100 MeV) (Hartman et al. 1999) and GeV source compilations (E > 1 GeV) (Lamb & Macomb 1997, Reimer et al. 1997), results from a total of 12 individual observations of 3EG J1835+5918 were reported. This source remained the brightest unidentified EGRET source outside the Galactic plane.

In order to extend the coverage of 3EG J1835+5918 to its maximum, we finally used all gamma-ray data taken by EGRET through the CGRO mission, including the observations made at a small off-axis angle in observation cycle 7. Generally one needs to distinguish between observations in which the angle between 3EG J1835+5918 and the instrument pointing direction was within or without 25°. This distinction has been recommended by the EGRET instrument team for using the standard PSF (sources within 25° of the instrumental pointing) or using the wide-angle PSF if outside. The EGRET observations from CGRO observation cycle 7 extend significantly beyond the catalogued observations. They are separated by more than 3 years from the previous observations of 3EG J1835+5918. Both the long-term observational aspect and the quality of the observation have been improved: despite the lower efficiency of the EGRET spark chamber, the 1998 observations were the first on-axis observations, unbiased from effects which most of the earlier EGRET observations of 3EG J1835+5918 could suffer from. The narrow field-of-view mode, used in EGRET viewing periods 710 and 711, does not introduce additional problems in this respect.

The best source location was obtained from EGRET’s highest energetic photons, where the instrumental PSF is significantly smaller than at lower energies. Using a likelihood method (Mattox et al. 1997, Reimer et al. 2001) determined the best position (> 1 GeV) to be $l = 88.80°$, $b = 25.02°$, which is consistent with the position from an analysis above 100 MeV ($l = 88.76°$, $b = 25.09°$), the posi-
tion given in 3EG and GeV catalogues, and the elliptical
fit from  
Mattox, Hartman & Reimer 2001
(  
l = 88.74°, b = 25.08°, a = 9.7°, b = 7.8°,  \Phi = 13°  ). However, the addi-
tional data gave positional errors of only 6° and 8° for the
68% and 95% confidence region, respectively.
Nolan et al. 1994 and  
McLaughlin et al. 1996
indicated flux variability for 3EG J1835+5918 on the basis of smaller
data sets than presented lastly. The most recent variabil-
ity study (  
Tompkins 1999
) puts 3EG J1835+5918 clearly
among the non-variable sources, similar to the identified
gamma-ray pulsars. Tompkins made use of an algorithm
especially adopted for the characteristics of the observa-
tions by EGRET, i.e. sparse data sets from individual ob-
ervations, often widely separated in time and character-
ized by different background levels. In addition, data from
individual EGRET observations up to CGRO observation
cycle 4 were used in this study. A strict data selection
(only within 25° on-axis) among the gamma-ray observa-
tions was used, assuring a data set of comparable quality.
We complemented the flux history of 3EG J1835+5918
with the data from 13-27 January 1998, the last high-
energy gamma-ray data on this source to be taken for
some years. Due to the generally lower efficiency of the
EGRET spark chamber towards the end of the EGRET
mission, the early 1998 viewing periods were evaluated us-
ing adjusted normalization factors  
Esposito et al. 1999.
These factors were checked quantitatively by means of a
similar on-axis observation of Geminga during 7-21 July
1998. Assuming that the instrumental sensitivity has not
changed appreciably between these observations and that
Geminga remains the stable gamma-ray emitter previ-
ously observed, this normalization for Geminga could be
applied to the flux of 3EG J1835+5918 in the cycle 7 ob-
servations. In addition, one needs to consider observations
with up to 25° off-axis separately from observations out-
side 25°. The fluxes above 100 MeV and above 1 GeV
appear to be linearly correlated, considering the uncer-
tainties in individual viewing periods arising from photon
statistics, especially for the sparse data of the detections
above 1 GeV.
We concluded, there is no indication of flux variability
after all for 3EG J1835+1918, neither above 100 MeV nor
above 1 GeV. Given the differing quality of the EGRET
observations within their statistical and systematical un-
certainties, we find 3EG J1835+5918 compatible with a
non-variable source of an average flux of $5.9 \times 10^{-7}$ cm$^{-2}$
$s^{-1}$ ($E > 100$ MeV).
After realizing that 3EG J1835+5918 is consistent with
having constant gamma-ray flux throughout the EGRET
mission, the issue of its spectral variability still remains.
Nolan et al. 1996 reported evidence for spectral vari-
ability between individual EGRET viewing periods. Ap-
parently, no correlation between spectral index and flux
was found. Hence, we re-examined the EGRET data on
3EG J1835+5918 for indication of spectral variability. In-
dividual spectra in each of the relevant viewing periods
were determined by simultaneously analyzing likelihood
excesses of 3σ detection significance and above. We de-
frived a flux value or upper limit in each of ten energy
intervals (30 MeV to 10 GeV) using a likelihood method.
In cases when poor count statistics gave a spectrum domi-
nated by upper limits, the ten energy intervals were recom-
bined into four (30-100, 100-300, 300-1000, >1000 MeV),
followed by the appropriate determination of the spectral
slope. Also, when the source position determined from
likelihood analysis of an individual observation differed
from the GeV-position, both positions were individually
considered for consequences for the resulting spectrum.
None of them introduces relevant modifications in the
resulting spectral slope. Therefore, the determined indi-
vidual spectra could be compared at the best level cur-
cently achievable for an unidentified high-energy gamma-
ray source.
We find that the spectra of 3EG J1835+5918 deter-
mained from individual viewing periods are fully compat-
ible within their statistical and systematic uncertainties
throughout the entire EGRET mission. A single power
law spectral index of 1.73 ± 0.07 is consistent within 1 σ
for all individual spectra.
With the consistency of the individual spectra
throughout the EGRET observations established, we co-
added the data from cycles 1 to 7 in order to determine
the best overall spectrum of 3EG J1835+5918. A single
power-law fit appears to be inadequate for this source. The
spectrum of 3EG J1835+5918 resembles the gamma-ray
spectra of known gamma-ray pulsars like Vela or Geminga
and the spectra of candidate gamma-ray pulsars 3EG
J2020+4017, 3EG J0010+7309, and 3EG J2227+6122: the
hard power law spectral index, as determined to be -1.7 ±
0.06 between 70 MeV and 4 GeV, the high-energy spectral
cut-off or turnover as well as a possible spectral softening
at the low energies. Upper limits from COMPTEL do not
constrain the shape of the spectrum at lower energies. The
TeV upper limits as reported by Whipple are consistent
with a rollover at 4 GeV, but certainly not with a simple
extrapolation of the EGRET measured power law spec-
trum to even higher energies.

2. Radio Observations
Deep searches in radio (770 MHz) at the position of
2EG J1835+59 could not detect any object above
0.5 Jy  
Nice & Sayer 1997.
This is in agreement with the correlation study between unidentified EGRET
sources and catalogued flat-spectrum radio sources (Green
Bank 4.85 GHz/Parkes-MIT-NRAO 4.85 GHz), not
suggesting any radio counterpart for 3EG J1835+59
  
Mattox, Hartman & Reimer 2001.

Fig. 1. The long ROSAT HRI (0.1 - 2.4 keV) observation of the field of 3EG J1835+5918 from December 1997/January 1998. The X-ray image is overlaid with source location contours (68% and 95%) of the high-energy gamma-ray source, determined above 1 GeV. The detected X-ray sources are indicated and were subject of a optical follow-on identification campaign.

3. X-Ray Observations

With the analysis of the 60 ksec ROSAT High Resolution Imager observation from December 1997/January 1998, the earlier coverage of this source in X-rays could be increased by a factor of 12. For the first time, counterparts have been discovered in X-rays between 0.1 -2.4 keV (Reimer et al. 1999). The sources are all faint with HRI count rates of 1-3 ksec$^{-1}$. Only sources 1 and 10 are excluded due to positional disagreement with the EGRET source, see Fig. 1.

4. Optical Observations

The discovered X-ray sources were subject of deep optical studies, performed at the 2.1 m telescope at the Guillermo Haro observatory at Cananea, Mexico. The instrumentation is aimed for ROSAT counterpart identifications and served well for our purpose. The observations were accompanied by studies of the DSS-2 images and use of the USNO A2.0 catalog. Independently, Halpern & Mirabal studied these counterparts at the 2.4 m Hilter telescope, the 3 m Shane reflector at Lick and the Hobby-Eberle telescope. The following optical counterparts were found:

1) positional disagreement, QSO with $z = 0.46$
2) QSO, $z = 1.87$
3) $U > 22.3, B > 23.4, V > 25.2, R > 24.5$
4) $V = 18.9, R = 19.2$, QSO with $z = 1.75$
5) $V = 19.3, R = 19.1$, QSO with $z = 1.865$
6) M5V star
7) QSO with $z = 1.36$
8) G7V dwarf star
9) bright object in center ($V = 15.6$), M type star, fainter object out of X-ray source error box, G type dwarf
10) K5V-star, in positional disagreement

5. Conclusions

3EG J1835+5918 is a persistent high-energy gamma-ray source located at high Galactic latitudes and has been observed repeatedly by EGRET. It is characterized by a hard power law and a spectral break or turn-over above 4 GeV. It appears to be a non-variable source in terms of its flux as well as its spectral shape throughout the entire EGRET mission, despite suggestions of variability from earlier analysis. Its gamma-ray properties are typical of those observed from other gamma-ray pulsars and candidate radio-quiet neutron stars. The deep ROSAT HRI observation revealed several X-ray sources consistent with the location of the observed GeV-emission of 3EG J1835+5918. As a result of the identification campaigns independently carried out by Mirabal & Halpern 2000 and ourselves, only one of the ten X-ray sources still attracts interest to be considered further for an association with the γ-ray source. This source, RX J1836.2+5925, is characterized by an obvious lack of radio-emission, indetectibility by means of an UV-excess identification technique, lack of optical counterpart up to $V \sim 25$ mag, and location well inside the 68% likelihood test statistic contours of 3EG J1835+5918. Our HRI observation contain no information on the X-ray spectrum of RX J1836.2+5925. Hence, assuming that this X-ray source is the most likely counterpart to 3EG J1835+5918, we are restricted to using the X-ray flux of RX J1836.2+5925 and the gamma-ray properties of 3EG J1835+5918 to investigate the characteristics of the object.

To do so, we can use its multi-frequency properties to ascertain its characteristics. The high $F_\gamma/F_{radio}$ value seems to rule out a blazar origin. The already noted similarities in the gamma-ray characteristics with known gamma-ray pulsars or radio-quiet pulsar candidates preferably suggests a neutron star nature for 3EG J1835+5918/RX J1836.2+5925. We have reexamined the gamma-ray and X-ray fluxes for all the known and candidate pulsars, using a consistent energy range in both bands. Comparing the flux of 3EG J1835+5918 in γ-rays ($E > 100$ MeV) and RX J1836.2+5925 in X-rays (0.12 - 2.4 keV), this source falls among the candidates currently considered for associations between gamma-ray sources and X-ray sources with proven or suspected neutron star origin, see Fig.5. Nearly all of the candidate gamma-ray pulsars lie at the bottom end of the sensitivity feasible for the last generation of X-ray instruments like...
 ROSAT, ASCA, and SAX. Obviously, only deep observations could reveal counterparts at all or with features not easily explained by any other astronomical objects. The lack of optical counterparts up to V~25 mag and radio emission for RX J1836.2+5925 is a further characteristic signature for isolated, radio-quiet neutron stars, and ideally demonstrated by Geminga as its gamma-ray bright prototype.

Although many of the candidate radio-quiet pulsars beside Geminga itself are located within or near SNRs, 3EG J1835+5918 does not. Neither radio observations nor the X-ray data yield any hint of a SNR in the vicinity of this object, and the high Galactic latitude seems to rule out the possibility of obscuration that might hide one.

If 3EG J1835+5918/RX J1836.2+5925 is not of quasar origin and also not the first candidate of an hypothesized extragalactic astronomical object bright and steady in gamma-rays, faint in X-rays, and yet undetectable at optical and radio wavelengths, it will reside within our Galaxy. We therefore have to suspect an isolated radio-quiet neutron star candidate. With Geminga as the only established pulsar of a predicted class of radio-quiet pulsars, a comparison of observational parameters in analogy with 3EG J1835+5918/RX J1836.2+5925 might be appropriate. Fig 2 compares the multi-frequency \( v F_ν \)-spectrum of Geminga and 3EG J1835+5918.

First, Geminga is three times brighter in gamma-rays and about fifty times brighter in X-rays. To extrapolate from the distance to Geminga using the observed fluxes, 3EG J1835+5918 would lie between 250 pc (scaling from gamma-rays) and 1.1 kpc (scaling from X-rays), assuming the same beaming as Geminga. Besides, pulsars tend to begin their life in the Galactic plane. A pulsar moving with a typical velocity of about 350 km/s would move only 300 pc, even in a lifetime of 106 years, while an object seen at b = 25° would have to move more than 420 pc from the plane if it were at a distance greater than 1 kpc. As pointed out by Yadigaroglu & Romani 1995 discussing the beaming evolution of pulsars in the outer-gap model, the beaming fraction becomes rather small as the pulsars age increases. Therefore a distant but old pulsar would have to be immensely powerful or exceptionally beamed. If 3EG J1835+5918 is more distant, then its gamma-ray luminosity would exceed that of Geminga, but if closer, then...
the surface brightness in X-rays of the neutron star would have to be lower than Gemingas. This indicates, that either the efficiency of the emission mechanism is different and/or the parameter space which radio-quiet pulsar candidates could occupy is widespread. In contrast to energetic pulsars like Vela or B1706-44, non-thermal emission or PWN features have not been observed here so far. Nor is it an extended source in X-rays. The lack of an associated SNR as well as the rare chance to find a similar pulsar at such high Galactic latitude (to say: nearby) argues against a young pulsar in the case of 3EG J1835+5918. However, the striking similarities in the gamma-ray properties between Geminga, other candidate radio-quiet pulsars and 3EG J1835+5918, the absence of a radio and optical counterpart of RX J1836.2+5925, points toward its nature of an old but radio-quiet neutron star.

Certainly, neither the X-ray data nor the gamma-ray data currently allow wide range period scans for pulsations without known ephemeris (Jones 1998, Chandler et al. 2001). Any (potentially) successful search for periodicity will have to be postponed until more sensitive instruments like XMM in the X-rays or GLAST in the gamma-rays will have observed 3EG J1835+5918. However, if a restrictive set of parameters can be predicted from pulsar models or if a lightcurve can be derived from another wavelength, the archival EGRET data will permit the discovery of pulsations in the gamma-rays. The long observational history presented here will certainly assist in any such effort. Finally, RX J1836.2+5925 might be identified as a neutron star by extremely deep optical imaging/spectroscopy, as already in progress using the Subaru telescope (Kawai et al. 2002).

To unambiguously relate 3EG J1835+5918 to a known class of astronomical objects would be of extreme importance for any collective studies of gamma-ray sources, and a gain for general pulsar physics if the existence of another isolated neutron star in gamma-rays will be confirmed.

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