Multifrequency studies of the enigmatic gamma-ray source 3EG J1835+5918

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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 which has not yet been identified. The 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 reanalysed 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. We especially address the question of flux and spectral variability, here discussed using the largest and most homogeneous data set available at high-energy gamma-rays for many years. The results from X-ray and gamma-ray observations were used in a follow-up optical identification campaign at the 2.2 m Guillermo Haro Telescope at Cananea, Mexico. VRI imaging has been performed at the positions of all of the X-ray counterpart candidates, and spectra were taken where applicable. The results of the multifrequency identification campaign toward this enigmatic unidentified gamma-ray source are given, especially on the one object which might be associated with the gamma-ray source 3EG J1835+5918. This object has the characteristics of an isolated neutron star and possibly of a radio-quiet pulsar.

Key words: Unidentified sources: gamma-rays: individual: 3EG J1835+5918 – gamma-rays: observations – X-rays: observations – optical observations: counterparts.

1 INTRODUCTION

The high-energy gamma-ray source 3EG J1835+5918 (also known as GRO J1837+59, 2EG J1835+5919, and GeV J1835+5921) has been of considerable interest since its discovery early in the CGRO mission by EGRET (Nolan et al. 1994). Unidentified sources at high-energy gamma-ray wavelengths present significant challenges today. The large error boxes preclude any simple identification based on positional association only. The absence of gamma-ray lines eliminates the possibility of making direct redshift or source composition measurements. In most cases, the photon statistics are inadequate to carry out conclusive periodicity searches. Even long-term time variability is hard to establish unless strong flaring behavior is seen. Multiwavelength studies have been one of the most useful identification techniques. The blazar-class Active Galactic Nuclei (AGN) seen by EGRET, for example, are characterized by strong radio emission (typically ~ 1 Jy at 5 GHz) and a spectral energy distribution (SED) with one peak at IR-UV frequencies and a second peak in the gamma-ray band. Gamma-ray pulsars have high $F_{\gamma}/F_{\text{radio}}$ and often $F_{\gamma}/F_X$ ratios, with a single clear SED peak in the hard X-ray to gamma-ray range. The energy requirements of gamma-ray production demand powerful sources; therefore ordinary stars and most normal galaxies can almost certainly be ruled out as gamma-ray sources.

3EG J1835+5918 is a bright gamma-ray source discovered at high Galactic latitudes by EGRET, and this source was not until recently identified with any plausible counterpart at other wavelengths. This has to be seen in respect to the observational fact that, other than 3EG J1835+5918, all of the bright gamma-ray sources at high Galactic latitudes have proved to be coincident with blazar-type AGN or flat spectrum radio quasars (FSRQ). However, even the most recent correlation of gamma-ray sources from the Third...
weak indication of flux variability was given. However, 3EG J1835+5919 yielded only a 1 mJy flux density upper limit (Nice & Sawyer 1997). At the neighboring wavelengths in gamma-rays, observations have yielded only upper limits for an object at the position of 3EG J1835+5918: the Whipple Telescope (E > 300 TeV) from observations made in 1993 (Kerrick et al. 1995), and COMPTEL (0.75 - 30 MeV) throughout their total exposure from 7 years of CGRO observations (Schönfelder et al. 2000). At the 5th Compton Symposium (Reimer et al. 2000, Carramiñana et al. 2000), we reported for the first time on X-ray counterparts for 3EG J1835+5918, suggesting an indication of a possible radio-quiet pulsar. An independent search by Mirabal et al. 2000 utilizing the same X-ray data, but separate optical observations, concluded instead that 3EG J1835+5918 was likely to be a prototype of a new type of high-energy gamma-ray source.* Here we report our final analysis of the EGRET, X-ray, and optical data. Our analysis reinforces our original conclusion that 3EG J1835+5918 has the characteristics of an isolated neutron star, possibly a Geminga-like radio-quiet pulsar.

2 THE EGRET SOURCE 3EG J1835+5918

3EG J1835+5918 was first discovered at photon energies above 100 MeV by the EGRET instrument aboard NASAs 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), most recently noted in Esposito et al. 1999. The first report on GRO J1835+59 (Nolan et al. 1994) included only data from EGRET observations between 1991 and 1993. On the basis of six analyzed viewing periods a weak indication of flux variability was given. However, 3EG J1835+5918 was only once observed at less than 20° off-axis. The authors noted that, under those circumstances, a factor of two flux variation is not a strong indication for flux variability. 3EG J1835+5918 is listed in the Second EGRET catalogue of gamma-ray point sources (Thompson et al. 1995), which utilized a similar set of viewing periods from CGRO observation cycles 1 and 2 as Nolan et al. 1994. A separate variability study including EGRET data from cycles 1 to 3 again reported the source as being variable (McLaughlin et al. 1996), but the determined value of the variability criterion (V = 1.3) lies in the range where this parameter is rather inconclusive in deciding whether or not a source is indeed variable. With the appearance of the Third EGRET catalogue (E > 100 MeV) and the GeV source compilations (E > 1 GeV) (Lamb & Macomb 1997, Reimer et al. 1997), results from a total of 12 individual observations of 3EG J1835+5919 were reported. The source remains the brightest unidentified EGRET source outside the Galactic plane. Furthermore, it has been documented that there is gamma-ray emission from 3EG J1835+5919 up to the highest energies observable by EGRET.

In order to extend the coverage of 3EG J1835+5919 to its maximum we use for the first time all gamma-ray data taken by EGRET through the CGRO mission, including the previously unpublished observations made at a small off-axis angle in observation cycle 7. Table 1 lists the EGRET observations of 3EG J1835+5918.

Throughout our analysis, we clearly 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.

In order to determine the most likely location of the gamma-ray source, we co-added the viewing periods using two different energetic thresholds (E > 100 MeV, and E > 1 GeV, respectively) and analyzed them individually. Because 3EG J1835+5918 is a strong emitter up to GeV-energies, the best source location was obtained from the highest energetic photons, where the instrumental PSF is significantly smaller than at lower energies. Using a likelihood method (Mattox et al. 1996), we determined the best position (> 1 GeV) to be l = 88.80°, b = 25.02°, which is consistent with the position of 3EG J1835+5918 from our analysis above 100 MeV (l = 88.76°, b = 25.09°), the position given in 3EG and GEV catalogues, and the elliptical fit from Mattox et al. 2001 (l = 88.74°, b = 25.08°, a = 9.7°, b = 7.8°, P = 13°). However, the additional data gave us positional errors of only 6' and 8' for the 68% and 95% confidence region, respectively. This enabled us to perform deep X-ray and optical studies of the entire region of 3EG J1835+5919. By using the position determined above 1 GeV, we examined the individual viewing periods in order to evaluate the long-term characteristic of the gamma-ray source flux. As discussed earlier, Nolan et al. (1994) and McLaughlin et al. (1996) indicated some source variability in 3EG J1835+5919 on the basis of smaller data sets than presented here. However, the most recent variability study (Tomkins 1999) puts 3EG J1835+5918 clearly among the nonvariable sources, similar to the identified gamma-ray pulsars. Tomkins made use of an algorithm especially adopted for the characteristics of the observations by EGRET, i.e. sparse data sets from individual observations, often widely separated in time and charac-

* Since this paper has been submitted, Mirabal and Halpern revised their earlier conclusion based on additional data, agreeing with the hypothesis that this source is most consistent with being a radio-quiet neutron star.
within 25 cycle were used in this study. A strict data selection (only individual EGRET observations up to CGRO observation characterized by different background levels. In addition, data from individual EGRET observations up to CGRO observation cycle were used in this study. A strict data selection (only within 25° on-axis) among the gamma-ray observations was used, assuring a data set of comparable quality. We complement 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, we still have to examine the issue of its instrumental sensitivity has not changed appreciably for Geminga could be applied to the flux of 3EG J1835+5918 in the cycle 7 observations. The light curve of 3EG J1835+5918 displaying all relevant EGRET observations is shown in Fig. 1, fluxes are for photon energies above 100 MeV, determined at the likelihood position of the GeV source. Also, when the source determination of the spectral slope. Therefore, the determination are marked differently. The lightcurve is consistent with a constant source considering statistical and instrumental restrictions from observations by the EGRET high-energy telescope.

We find that the spectra of 3EG J1835+5918 determined by simultaneously analyzing likelihood excesses of 3 σ detection significance and above. We derived 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 dominated by upper limits, the ten energy intervals were recombined 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 individual spectra could be compared at the best level currently achievable for an unidentified high-energy gamma-ray source.

We find that the spectra of 3EG J1835+5918 determined from individual viewing periods are fully compatible within their statistical and systematic uncertainties throughout the entire EGRET mission, see Figure 2. 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

| Viewing Period | Start Date | End Date | Aspect [°] | σ (> 100 MeV) | σ (> 1 GeV) | comment |
|----------------|------------|----------|------------|---------------|-------------|---------|
| 0020           | 05/30/91   | 06/08/91 | 27.00      | 4.8           | 3.9         | outside 25° |
| 0092           | 09/12/91   | 09/19/91 | 28.61      | 4.4           | 4.5         | outside 25° |
| 0220           | 03/05/92   | 03/19/92 | 27.30      | 4.1           | 1.4         | outside 25° |
| 2010           | 11/17/92   | 11/24/92 | 23.28      | 5.1           | 1.2         |         |
| 2020           | 11/24/92   | 12/01/92 | 21.46      | 6.3           | 5.2         |         |
| 2030           | 12/01/92   | 12/22/92 | 26.55      | 9.3           | 5.1         | outside 25° |
| 2120           | 03/09/93   | 03/23/93 | 14.21      | 9.6           | 9.4         |         |
| 3020           | 09/07/93   | 09/09/93 | 17.25      | 2.5           | u.l.        |         |
| 3032           | 09/22/93   | 10/01/93 | 17.25      | 7.5           | 6.7         |         |
| 3034           | 10/01/93   | 10/04/93 | 22.07      | 3.3           | 4.8         |         |
| 3037           | 10/17/93   | 10/19/93 | 17.25      | u.l.          | u.l.        |         |
| 4030           | 11/01/94   | 11/09/94 | 28.78      | u.l.          | u.l.        | outside 25° |
| 7100           | 01/13/98   | 01/21/98 | 5.03       | 5.4           | 3.4         |         |
| 7110           | 01/21/98   | 01/27/98 | 5.03       | 5.6           | 6.1         |         |
| co-added        |            |          |            | 20.1          | 15.3        |         |

Table 1. γ-ray observations of 3EG J1835+5919.

Figure 1. Gamma-ray flux history of 3EG J1835+5918. The fluxes (E >100 MeV) of 3EG J1835+5918, derived from data taken between 1991 and 1998. To assure comparable quality in the data, observations within or without 25° of the target direction are marked differently. The lightcurve is consistent with a constant source considering statistical and instrumental restrictions from observations by the EGRET high-energy telescope.

determined by simultaneously analyzing likelihood excesses of 3 σ detection significance and above. We derived 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 dominated by upper limits, the ten energy intervals were recombined 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 individual spectra could be compared at the best level currently achievable for an unidentified high-energy gamma-ray source.

We find that the spectra of 3EG J1835+5918 determined from individual viewing periods are fully compatible within their statistical and systematic uncertainties throughout the entire EGRET mission, see Figure 2. 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
between 1991 and 1998. The high-energy gamma-ray spectrum of 3EG J1835+5918 has been reported earlier to be variable. However, we find that the uncertainties in the determination of the spectrum only allow us to conclude, that the spectrum of 3EG J1835+5918 is still in agreement with being constant at a one sigma level throughout the entire EGRET coverage between 1991 and 1998. To emphasize comparable quality in the data, observations within or without 25° of the target direction are marked differently as in Figure 1.

Figure 2. The gamma-ray spectral index of 3EG J1835+5918 between 1991 and 1998. The high-energy gamma-ray spectrum of 3EG J1835+5918 has been reported earlier to be variable. However, we find that the uncertainties in the determination of the spectrum only allow us to conclude, that the spectrum of 3EG J1835+5918 is still in agreement with being constant at a one sigma level throughout the entire EGRET coverage between 1991 and 1998. To emphasize comparable quality in the data, observations within or without 25° of the target direction are marked differently as in Figure 1.

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 (Thompson et al. 1997) and the spectra of candidate gamma-ray pulsars like 3EG J0010+7309, as can be seen in Fig. 3; the hard power law spectral index, as determined to be -1.7 ± 0.06 between 70 MeV and 4 GeV, the high-energy spectral cutoff or turnover as well as a possible spectral softening at the low energies. The restriction in energy when applying a single power law fit takes these features into account: it is based on the bins with the highest instrumental sensitivity. The upper limits from COMPTEL (Schönfelder 2000) do not constrain the shape of the spectrum at lower energies. The TeV upper limits as reported by Kerrick et al. (1995) could be verified and corrected. Deep follow-up observations from a single power-law model are seen at the lowest and highest energies.

3 X-RAY OBSERVATIONS OF 3EG J1835+5918

The first observation towards 3EG J1835+5918 took place in February 1995. A 9 ksec ROSAT HRI observation was performed, which reached a minimum detectibility limit of about 8 × 10^{-14} erg cm^{-2} s^{-1} in the 0.1 to 2.4 keV band. A longer HRI observation was taken in December 1997/January 1998 as proposed by us in the ROSAT guest observer program. It exceeded the exposure of the former HRI observation by a factor of six with a total of 61,269 kseconds. Assuming a power-law spectrum with a photon index of -2 and a Galactic hydrogen column density of N_H=5 × 10^{20} cm^{-2}, the limiting unabsorbed X-ray flux is about 2 × 10^{-14} erg cm^{-2} s^{-1}. Table 2 lists the detected X-ray sources in the long ROSAT HRI observation before astrometric corrections were applied. The astrometric correction is discussed in the context of reliable optical counterparts, see next section. Figure 4 shows the ROSAT HRI image, with the individual sources marked. Overlaid is the gamma-ray source location contour, determined solely from photons with energies above 1 GeV. The contours represent the 68% and 95% likelihood boundaries of the source location.

Only three of the ten sources found in this deeper HRI observations were detected in the earlier, short HRI observation (objects 1,3,9). We only note this here because the one object of further interest after investigating the deep HRI image, RX J1836.2+5925, is rather close to the detection limit of the short observation. When examining X-ray variability for this particular source, it is generally hard to conclude based on two detections only, especially with one relatively close to its detection limit. However, any report on X-ray source variability would push the interpretations rather hard into some unique direction. Therefore we make no conclusions on the variability until further observations have been made and analyzed.

The most recent X-ray observation took place between April 20-22, 1998, performed by ASCAs GIS and SIS detectors. The SIS data did not detect any object in the vicinity of 3EG J1835+5918, and the detected sources from the stacked GIS-images are located outside the GeV-source location we consider. There are no constraints from the nondetection of X-ray sources in the SIS images compared to the sensitivity achieved from the deep HRI observation.

Figure 3. The high-energy gamma-ray spectrum of the source 3EG J1835+5918, derived from data taken between 1991 and 1998. The power-law model fit was determined between photon energies of 70 MeV and 4 GeV, where this fit was applicable. Deviations from a single power-law model are seen at the lowest and highest energies.

4 OPTICAL IDENTIFICATIONS IN THE VICINITY OF 3EG J1835+5918

We studied the X-ray sources found in the vicinity of 3EG J1835+5918 for optical counterparts. If objects at optical wavelengths appear coincident at positions of the X-ray sources, the astrometry of the obtained ROSAT HRI-image could be verified and corrected. Deep follow-up observations have been conducted in order to conclude on the nature of those optical counterparts. Starting with a general assessment on the basis of DSS-2 plates and USNO-A2.0 catalogue listings, we subsequently performed VRI imaging of
Table 2. Sources detected in the 60 ks ROSAT HRI X-ray observation and and their relation to 3EG J1835+5918

| No | Name (J2000) | RA (J2000) | DEC (J2000) | Identification | Association with 3EG J1835+5918 |
|----|--------------|------------|-------------|---------------|---------------------------------|
| 1  | RX J1837.0+5934 | 18h 37m 00.82s | +59° 34′ 20.5″ | QSO (z ≃ 0.47) | highly unlikely |
| 2  | RX J1835.9+5926 | 18h 35m 58.09s | +59° 26′ 18.0″ | QSO (z = 1.87) | unlikely |
| 3  | RX J1836.2+5925 | 18h 36m 13.62s | +59° 25′ 28.9″ | n.a. | candidate |
| 4  | RX J1836.6+5924 | 18h 36m 38.45s | +59° 27′ 24.0″ | QSO (z = 1.75) | unlikely |
| 5  | RX J1835.9+5923 | 18h 35m 53.32s | +59° 27′ 29.0″ | QSO (z = 1.86) | unlikely |
| 6  | RX J1834.4+5920 | 18h 34m 23.82s | +59° 20′ 51.0″ | M5V star | highly unlikely |
| 7  | RX J1836.6+5920 | 18h 36m 36.78s | +59° 20′ 40.6″ | QSO (z = 1.36) | unlikely |
| 8  | RX J1834.2+5920 | 18h 34m 14.23s | +59° 20′ 24.5″ | G7V star | highly unlikely |
| 9  | RX J1835.5+5915 | 18h 35m 32.33s | +59° 15′ 39.3″ | M star | highly unlikely |
| 10 | RX J1836.8+5910 | 18h 36m 50.81s | +59° 10′ 03.7″ | K5V star | highly unlikely |

Figure 4. 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.

the entire field of the gamma-ray source at the Observatorio Astrofisico Guillermo Haro, located in Cananea, Sonora (lat=31°, long=110° W). We used the Faint Object Spectrograph Camera (LFOSC) of the Landessternwarte Heidelberg, specially designed for optical counterpart identifications. The instrument allows photometric BVRI imaging in a 10′ x 6′ FOV and two modes of low-resolution spectroscopy. Observations in July and September 1997, and May 1998 were devoted to VRI imaging. When the ROSAT HRI image taken at January 1998 had been delivered and thoroughly analyzed, spectroscopy was made in June and October 1999 by using the low resolution mode at 4200Å to 9000Å with a ∼8.3Å/pixel sampling.

Fortunately, the search for counterparts has revealed one excellent astrometrical measure in the field, a star listed in the Tycho-2 (3917 00934 1) and ACT-catalogues. The offset of the coincident X-ray object 8 (RX J1834.2+5920) is about 0.5 s in right ascension and 1.1″ in declination. A similar offset has been found at the USNO-A2.0 listed object coincident with the X-ray object 5 (RX J1835.9+5923). Offsets at other object pairs differ more, significantly at the edge of the field of view. Therefore we do not average any additional, in some cases contradictory offset parameter. We apply the correction found appropriate for object 8 and 5 throughout the entire HRI image. The following objects were studied:

(1) RX J1837.0+5934: This X-ray source is outside the 68% and 95% GeV error contour, already signalling that an association is unlikely. Two USNO-A2.0 listed objects are positionally consistent with the X-ray source position. The optical spectrum of the brighter object shows a strong emission line at 7198Å which can be identified as redshifted Hβ, allowing us to associate the emission lines at 6364Å and 6012Å with reshifted Hγ and Hδ. This quasar at z ≃ 0.46 is a very plausible counterpart for the X-ray source.

(2) RX J1835.9+5926: An optical object, located 7″ NE from the X-ray source position has been found at the Cananea images (V > 20.2; R = 20.5±0.7). Its final identification with a QSO at z = 1.87 by Mirabal et al. 2000 is plausible.

(3) RX J1836.2+5925: Two faint objects are at 11″ NW and 14″ SE of the X-ray source location, not listed in the USNO-A2.0. Given the low uncertainty on the X-ray position, an association between either of them and the ROSAT source is doubtful. Our images have a detection limit around R > 21, and no other object is found anywhere closer to the X-ray source position.

(4) RX J1836.6+5924: An optical object (V=19.0±0.2, R=19.5±0.2) lies centered on the X-ray position. It has been identified with a QSO at z = 1.75 by Mirabal et al. 2000.

(5) RX J1835.9+5923: The optical object nearly centered at the X-ray position (V=19.3±0.3, R=19.1±0.2) shows a strong emission line, which we identify with CIV1550, recovering CIV1909 redshifted to 5469Å. This quasar at z ≃ 1.865 is highly unlikely to be the X-ray emitting source.

(6) RX J1834.4+5920: An optical object is more than 10″ distant from the X-ray position for which we measured V=18.04±0.10 and R=18.0±0.10. Its spectrum indicates a late type star, probably M5V. This X-ray source is 1.3″ from the bright star coincident with X-ray source number 8, whose glow complicates the detection of objects fainter than magnitude 20. The potential identification of the M5V star with the X-ray source would rule out their association with the 3EG J1835+5918. If one does not follow this identification scheme due to the source location offset, we find no other optical counterpart for this object. However, this
would leave the question unanswered, why we observe no X-ray emission from this M5-star down to the detection limit of the ROSAT HRI image.

(7) RX J1836.6+5920: There is no optical object brighter than V=21 inside the error box. Mirabal et al. 2000 found an optical object at B=21.3 at z=1.36 by a UV-excess selection technique using the Hobby-Eberly Telescope. Although, we cannot adopt their argument of rejection by positional inconsistency of RX J1836.6+5920 with the EGRET-source location contour, the optical and X-ray properties of this QSO would make it highly unlikely to be the counterpart of 3EG J1835+5918.

(8) RX J1834.2+5920: The star Tycho 391700341 with V∼9.4 is centered at the X-ray source position. The spectrum obtained indicates a late G dwarf star, probably G7V.

(9) RX J1835.5+5915: A V = 15.6 magnitude object is about 5′ from the X-ray position, and therefore marginally consistent with the X-ray source. Its spectrum indicates a late M-type star.

(10) RX J1838.8+5910 is outside the 68% and 95% location contour of the EGRET source, and their physical association is practically rejected on positional inconsistency. A bright star V∼11th magnitude (Tycho 3917018071) is coincident with the X-ray position. Our spectrum indicates a K star, probably K5V.

We reject only sources 1 and 10 primarily on the grounds of inconsistency with the GeV source location. If this argument does not absolutely disqualify both X-ray sources as candidates for an association with the gamma-ray source, their identifications probably do. Also, the identified coronal emitting stars do not qualify as likely counterparts for 3EG J1835+5918. The four QSO-identifications (z=1.36, 1.75, 1.87, 1.86) certainly need a closer look. First of all, these are not blazar-class AGN which constitute the vast majority of the known EGRET QSO sources. Also, their redshifts would lie at the tail of the redshift-distribution of gamma-ray loud Active Galactic Nuclei (Mukherjee 1997). The lack of observed radio emission is an additional hint that they do not belong to the class of AGN that EGRET could actually see (Mattox et al. 2001). The obvious mismatch between one of the brightest gamma-ray sources at high Galactic latitudes and the lack of observable radio emission would exhibit 3EG J1835+5918 as a unique source among the gamma-ray sources identified with active galactic nuclei. Secondly, the intrinsic gamma-ray emission characteristics argue against a quasar counterpart. The EGRET-detected AGN are highly variable at all timescales currently observable. The average spectral index of the EGRET-detected AGN is significant softer than the one determined for 3EG J1835+5918, in fact it would put 3EG J1835+5918 as the hardest source among the more than ninety EGRET-detected AGNs. The lack of obvious source variability as well as the hard spectral index of 1.7 ± 0.06 would solely argue against a quasar identification; both arguments together do so with a rather high degree of confidence. Parameters like the optical to X-ray and/or optical to γ-ray luminosity ratio for the QSO-counterparts do not give a unique signature. The range which could be occupied by QSOs in both parameter spaces is rather wide. Also, the correlation signatures reported for 61 of the gamma-ray loud blazars (Cheng et al. 2000) do not allow any additional conclusive information for the four X-ray sources identified as radio-quiet QSOs. Summarizing, the various observational facts concerning an association between each of the X-ray sources identified as quasars and the unidentified gamma-ray source 3EG J1835+5918 do not support such an interpretation. More exotic scenarios must be called in order to accept one of the quasar identifications, like hypothesized radio-quiet blazars (Mannheim 1993) or a γ-ray AGN with a shifted SED (Ghisellini 1999), where the synchrotron component will fall in the MeVs and the IC-component peaks at TeV-energies. Currently, observational constraints from COMPTEL and Whipple do not indicate that the SED peaks at any other wavelength band except where 3EG J1835+5918 is observable, bright and steady: the 30 MeV to 10 GeV band where EGRET operated for nine years.

Therefore, we have to consider further only one X-ray source in the vicinity of 3EG J1835+5918, RX J1836.2+5925 (object 3, see Table 2). The lack of an optical counterpart and therefore of the possibility to identify it by means of an optical spectrum keeps this source as the only unidentified X-ray source which could have an association with the γ-ray source 3EG J1835+5918. Using their independent optical observation, Mirabal et al. 2000 also concluded that RX J1836.2+5925 is the most probable X-ray counterpart to the gamma-ray source.

**DISCUSSION**

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 nonvariable source in terms of its flux as well as its spectral shape throughout the entire EGRET mission, despite suggestions of variability from earlier analyses. Its gamma-ray properties are typical of those observed from gamma-ray pulsars like Vela or Geminga, and candidate radio-quiet pulsars like 3EG J2020+4017, 3EG J0010+7309, and 3EG J2227+6122. Our 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 et al. 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, indeetectability by means of an UV-excess identification technique, lack of optical counterpart up to V∼23 mag in the V- and B-bands, 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 multifrequency properties to ascertain its characteristics. The high $F_{\text{X}}/F_{\text{radio}}$ value seems to rule out a blazar origin. The already noted similarities in the gamma-ray characteristics with known gamma-ray pulsars (Thompson et al. 1997) or radio-quiet pulsar candidates (for a recent summary, see Brazier & Johnston 1999) definitely
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, extremely well characterized with its highly resolved high-energy lightcurve, independent measurements of rather weak radio emission and a faint optical counterpart with noticeable proper motion, a comparison of observational parameters in analogy with 3EG J1835+5918/RX J1836.2+5925 might be appropriate. First, Geminga is three times brighter in gamma-rays and about fifty times brighter in X-rays. To extrapolate from the distance to Geminga (d \gtrsim 160 pc, Caraveo et al. 1996) 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 in both cases. Besides, pulsars tend to begin their life in the Galactic plane. A pulsar moving with a typical velocity of about 350 km s\(^{-1}\) would move only 300 pc even in a lifetime of 10\(^6\) years, while an object seen at \(b = 25^\circ\) 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 Yardagcroglu and Romani (1995) discussing the beaming evolution of pulsars in an 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 were more distant, then its gamma-ray luminosity would exceed that of Geminga, but if it were closer, then the surface brightness in X-rays of the neutron star would have to be lower than Geminga. 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 wide spread. In contrast to energetic pulsars like Vela or B1706-44, nonthermal emission or pulsar nebular features have not been observed in the case of RX J1836.2+5925 so far. Nor is it an extended source in the X-rays. The lack of an associated SNR as well as the rare chance to find a similar pulsar at such high Galactic latitude (i.e. 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, and, finally, the arrangement of 3EG J1835+5918/RX J1836.2+5925 among the other candidate gamma-ray pulsars (Fig. 5) still leaves room for accepting a hypothesis being an older but radio-quiet pulsar.

Halpern et al. 2000 hypothesized in the case of 3EG J2227+6122/RX J2229.0+6114 a medium aged gamma-ray pulsar population, efficient enough to be comparable to older pulsars like Geminga or B1055-52, although matching the luminosity (i.e. spin-down power) constraints from gamma-ray observations. With 3EG J2227+6122/RX J2229.0+6114

![Figure 5. X-ray and gamma-ray fluxes of high-confidence pulsar detections (filled circles), probable associations between pulsars and high-energy gamma-ray sources (open circles), and candidate radio-quiet pulsars (filled squares). All X-ray fluxes are given for the 0.1 to 2.4 keV energy band, in cases of different energy band quoted in the literature (Crab, B1509-58, B1951+32, B1046-58 from Becker & Trüper 1997, SAX J0635+0533 from Kaaret et al. 1999, AX J1420.1-6049 from Roberts et al. 2000, J0218+4332 from Kuiper et al. 1998), the flux is normalized into the chosen energy band. The gamma-ray fluxes are given above 100 MeV, in cases where different event selection criteria were used (B0656+14: > 50 MeV (Ramanamurthy et al. 1995), B1046-58: > 400 MeV (Kaspi et al. 2000), B1509-58: 30 to 100 MeV (Kuiper et al. 1999), J0218+4332: 100 to 300 MeV (Kuiper et al. 2000)) the appropriate gamma-ray flux above 100 MeV has been determined for the energy band desired here.](image-url)
rather close in its \( F_\gamma / F_X \) to young pulsars with nonthermal emission and pulsar nebular features, 3EG J1835+5918/RX J1836.2+5925 lies well among the other candidate radio-quiet pulsars. We rather stress the similarities seen in the \( F_\gamma / F_X \) to existing candidate gamma-ray pulsars, together with its characterization by apparently similar gamma-ray properties as identified pulsars, however faint in X-rays and with no counterpart yet at optical and radio frequencies. Mirabal and Halpern (2001) have recently reached a similar conclusion.

With 3EG J1835+5918/RX J1836.2+5925 being in the range of a isolated neutron star candidate explanation, other suggestions still need to be looked at. A similarity to the widely discussed association between LSI +61\(^\circ\)303/3EG J0241+6103 and SAX J0635+533/3EG J0634+0521 does not seem to be appropriate for various and strict reasons. Both are binary systems (Be/X-ray), characterized by different states of variability on all but the shortest timescales. Also, they show a gamma-ray spectrum significantly softer than determined in the case 3EG J1835+5918. Most severe, since only a small number of such Be/X-ray binaries is expected (Vanbeveren et al. 1998), the high Galactic location of 3EG J1835+5918 would indicate a rather nearby one, definitely conflicting with the lack of any optical counterpart up to 23rd magnitude. With extremely high degree of confidence we can therefore rule out the probability of seeing a massive star/compact object binary system here.

There have been other suggestions made for 3EG J1835+5918. Plaga et al. 1999 explicitly refer to 3EG J1835+5918 as an example for a hot-spot of a Galactic gamma-ray burst. The low X-ray luminosity of RX J1836.2+5925 and the upper limit from the Whipple observation are severe observational arguments against such a hypothesis. Isolated accreting black holes (Armitage & Natarajan 1999) were suggested to be energetically consistent with unidentified sources at all Galactic latitudes. However, if their high energy emission occurs via similar processes to those in AGNs, it is expected to observe variability on all timescales. This is definitely not the case for 3EG J1835+1918. The persistent nature of the detections from 3EG J1835+5918 also excludes any similarities to gamma-ray transient like GRO J1838-04.

Certainly, neither the X-ray data nor the gamma-ray data currently allow wide range period scans for pulsations without known ephemerides (Jones 1998). A search for periodicity will have to be postponed until more sensitive instruments like XMM in the X-rays or GLAST in the gamma-rays 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. 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, as well as for studies of contributors to the diffuse gamma-ray background, not to mention the gain for pulsar physics if the existence of another isolated neutron star in gamma-rays is confirmed.

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