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A NEUTRON-STAR IDENTIFICATION FOR THE HIGH-ENERGY GAMMA-RAY SOURCE 3EG J1835+5918 DETECTED IN THE *ROSAT* ALL-SKY SURVEY

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ABSTRACT

In the error box of 3EG J1835+5918, the brightest as-yet unidentified EGRET source at intermediate Galactic latitude, we find a weak, ultrasoft X-ray source at energies $E < 0.3$ keV in the *ROSAT* All-Sky Survey. Deep optical imaging at the location of this source, as pinpointed by an observation with the *ROSAT* HRI, reveals a blank field to a limit of $V > 25.2$. The corresponding lower limit on f_X/f_V is 300, which signifies that the X-ray source is probably a thermally emitting neutron star. Considering our previous complete multiwavelength survey of the 3EG J1835+5918 region which failed to find any other notable candidate for identification with 3EG J1835+5918, we propose that this X-ray source, RX J1836.2+5925, is a rotation-powered γ -ray pulsar which is either older or more distant than the prototype Geminga. We see marginal evidence for variability between two *ROSAT* HRI observations. If real, this would indicate that the X-ray emission has an external origin, perhaps due to intermittent heating of the polar caps by a variable particle accelerator. RX J1836.2+5925 could even be an old, recycled pulsar, which may nevertheless have a high γ -ray efficiency.

Subject headings: gamma rays: observations — stars: neutron — X-rays: individual (RX J1836.2+5925)

1. INTRODUCTION

The nature of the persistent high-energy (> 100 MeV) γ -ray sources in the Galaxy remains an enigma three decades after their discovery. Ever since the identification of the mysterious γ -ray source Geminga as the first radio quiet but otherwise ordinary pulsar (see review by Bignami & Caraveo 1996), it has been argued that rotation-powered pulsars likely dominate the Galactic γ -ray source population (e.g., Yadigaroglu & Romani 1997), and that many of them will be radio quiet. That Geminga is a bright EGRET source at a distance of only ~ 160 pc (Carveo et al. 1996) begs for it not to be unique.

Several excellent neutron-star candidates for EGRET sources have emerged from X-ray observations in recent years. One is present in the supernova remnant CTA1 which is close to 3EG J0010+7309 (Brazier et al. 1998). Another is in the γ -Cygni supernova remnant which is coincident with 3EG J2020+4017 (Brazier et al. 1996). An intriguing 34 ms X-ray pulsar with a Be star companion lies in the error circle of 3EG J0634+0521 (Kaaret et al. 2000). X-ray nebulae that are inferred to contain pulsars have been detected in the error circles of the EGRET sources 2EG J1811–2339 (Oka et al. 1999) and 3EG J1420–6038 (Roberts & Romani 1998; Roberts et al. 1999). Radio-quiet neutron stars have been found which are not apparently EGRET sources, but they are important as members of the growing class of cooling neutron stars (RX J185635–3754, Walter 2000; PKS 1209–52, Zavlín et al. 2000). Neutron-star candidates discovered by *ROSAT* were reviewed by Caraveo, Bignami, & Trümper (1996) and by Motch (2000).

As the brightest of the as-yet unidentified intermediate-latitude EGRET sources at $(\ell, b) = (89^\circ, 25^\circ)$, 3EG J1835+5918 is a good *a priori* target for the next such identification. We recently completed an exhaustive

search for a counterpart of 3EG J1835+5918. The observations included deep radio, X-ray, and optical surveys, as well as optical spectroscopic classification of every active object within or close to its 99% confidence error ellipse (Mirabal et al. 2000, hereafter Paper 1). In summary, we identified optically all but one of the *ROSAT* and *ASCA* sources in the region of 3EG J1835+5918 to a flux limit of $\sim 5 \times 10^{-14}$ erg cm⁻² s⁻¹, which is 10^{-4} of the γ -ray flux, without finding any suggestive evidence for a possible counterpart among the identified sources. We also proposed that the one unidentified X-ray source, RX J1836.2+5925, is the most promising candidate for identification with 3EG J1835+5918 principally because the *absence* of an optical counterpart for it is the standard signature of an isolated neutron star, or perhaps a more exotic compact object.

The recent release of the decade-old *ROSAT* All-Sky Survey (*RASS*) data (Voges et al. 2000) provides an important new tool for detecting neutron stars by means of their soft, thermal X-ray emission, and thus for furthering the search for the counterparts of nearby EGRET sources. In this Letter, we report new results from the *RASS* on the previous candidate RX J1836.2+5925 which greatly enhance its credentials as the likely pulsar counterpart of 3EG J1835+5918. We also present a detailed study of the X-ray and optical objects in its immediate neighborhood which establishes that RX J1836.2+5925 is indeed undetected to a limit of $V > 25.2$, as would be expected for a neutron-star counterpart of 3EG J1835+5918.

2. X-RAY OBSERVATIONS OF RX J1836.2+5925

A total of four X-ray observations that cover the entire 99% error ellipse of 3EG J1835+5918 have been made

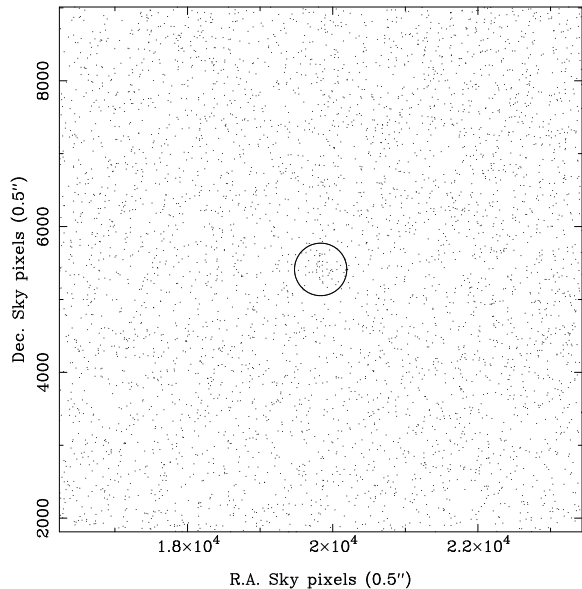


FIG. 1.— A photon map of the $1^\circ \times 1^\circ$ region around RX J1836.2+5925 from the *ROSAT* All-Sky Survey. Only events with pulse heights in the range 0.1–0.35 keV are shown. The net, background subtracted counts from RX J1836.2+5925 number 22.3 ± 6.3 .

to date, one by the *RASS* with the PSPC instrument, two by the *ROSAT* High Resolution Imager (HRI), and one by the *ASCA* GIS. The dates and exposure times of these observations are listed in Table 1. The results of the two pointed *ROSAT* observations and the one *ASCA* observation were presented in Paper 1, and they will not be repeated here except where relevant to the properties of RX J1836.2+5925.

In the *RASS* Faint Source Catalog, we find an entry at the position (J2000) $18^{\text{h}}36^{\text{m}}13^{\text{s}}.59$, $+59^\circ25'30''.5$ with an uncertainty of $26''$ and a count rate of $0.0146 \pm 0.0041 \text{ s}^{-1}$. The effective exposure time at this location was 1532 s. The hardness ratio of the source is given as -1.0 , meaning that all of its photons fall at energies below 0.4 keV. This source is consistent in position and flux with the later observed *ROSAT* HRI source RX J1836.2+5925 as described in Paper 1, and since it is by far the brightest source within a region of radius $10'$ there is no reason to suspect confusion with the many fainter HRI sources in its vicinity. An image of the source and its surrounding field in the *RASS* is shown in Figure 1.

A deep X-ray image of the field around RX J1836.2+5925, taken from the longer *ROSAT* HRI observation, is shown in Figure 2. RX J1836.2+5925 is the brightest source in this Figure. Six of the fainter X-ray sources were identified using multicolor CCD imaging and optical spectroscopy. Their positions and counterparts are given in Table 1 of Paper 1. We use these sources to tie the X-ray positions to the optical astrometric reference frame employed by the USNO-A2.0 catalog (Monet et al. 1996). Figure 3 shows the offsets between the X-ray positions and the optical positions before and after a zero-point shift was applied to the X-ray positions in order to correct a small systematic error which is hardly apparent in the individual identifications. This offset is only $1''.3$ in right ascension and $0''.8$ in declination. The final error circle

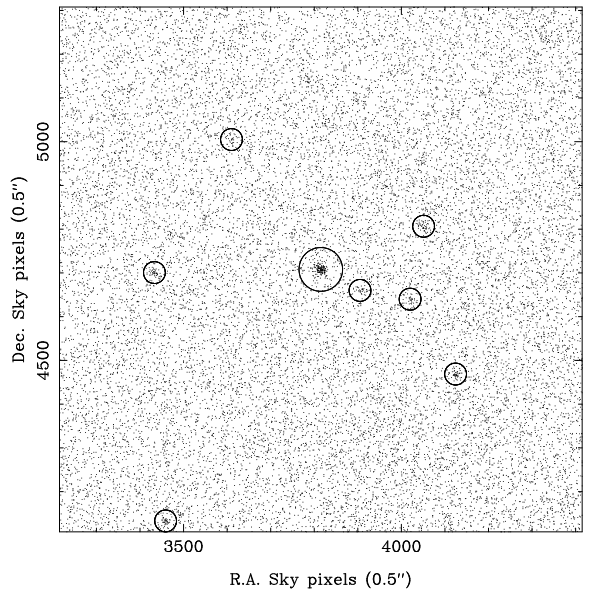


FIG. 2.— A $10' \times 10'$ portion of the *ROSAT* HRI image centered on the brightest, unidentified X-ray source RX J1836.2+5925 (large circle). As refined with the help of Figure 3, the position of RX J1836.2+5925 is (J2000) $18^{\text{h}}36^{\text{m}}13^{\text{s}}.77$, $+59^\circ25'30''.4$.

radius of $3''$ includes all of the X-ray source identifications in Figure 3, and it is undoubtedly a conservative estimate of the positional error of the bright unidentified source RX J1836.2+5925. The corrected position for the latter is (J2000) $18^{\text{h}}36^{\text{m}}13^{\text{s}}.77$, $+59^\circ25'30''.4$. We adopt this as the best X-ray position. It differs by only $1''.5$ from the position given in Paper 1, and it agrees very well with the position of the corresponding *RASS* source.

We further examined the nature of RX J1836.2+5925 in the *RASS* by extracting source photons from within a radius of $3'$, and obtaining a background estimate from an annulus of inner radius $4'$ and outer radius $8'$. Although this source contains only 22 net photons it is clearly real; Voges et al. (2000) give a probability of 3×10^{-7} that it is spurious. By binning the photons into pulse-height intervals of 0.1 keV, we see that there is no evidence for any emission above 0.3 keV (see Table 2). If fitted by a blackbody model, such a pulse-height distribution is consistent with $T \leq 5 \times 10^5 \text{ K}$, but it is also dependent upon the unknown intervening column density. If we assume $1 \times 10^{20} < N_{\text{H}} < 3 \times 10^{20} \text{ cm}^{-2}$, the bolometric flux corresponding to an assumed $T = 5 \times 10^5 \text{ K}$ is in the range $(1.5 - 5.7) \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$. The soft spectrum of this source also explains why it was not detected in the *ASCA* observation, which had a 1–10 keV detection limit of $\sim 1 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$.

The net count rate of RX J1836.2+5925 in the *ROSAT* HRI observation of 1998 is $(2.25 \pm 0.23) \times 10^{-3} \text{ s}^{-1}$. For the spectral parameters assumed above, the HRI flux agrees with the PSPC flux measured 7.5 yr earlier to better than 10%. Although this is consistent with a thermal neutron star interpretation, the source was possibly *not* detected in the shorter HRI observation in 1995. The formal count rate in the latter observation was only $(0.90 \pm 0.51) \times 10^{-3} \text{ s}^{-1}$. Because of the small number of photons detected, the significance of the variability should be evaluated using Poisson statistics. In this analysis we

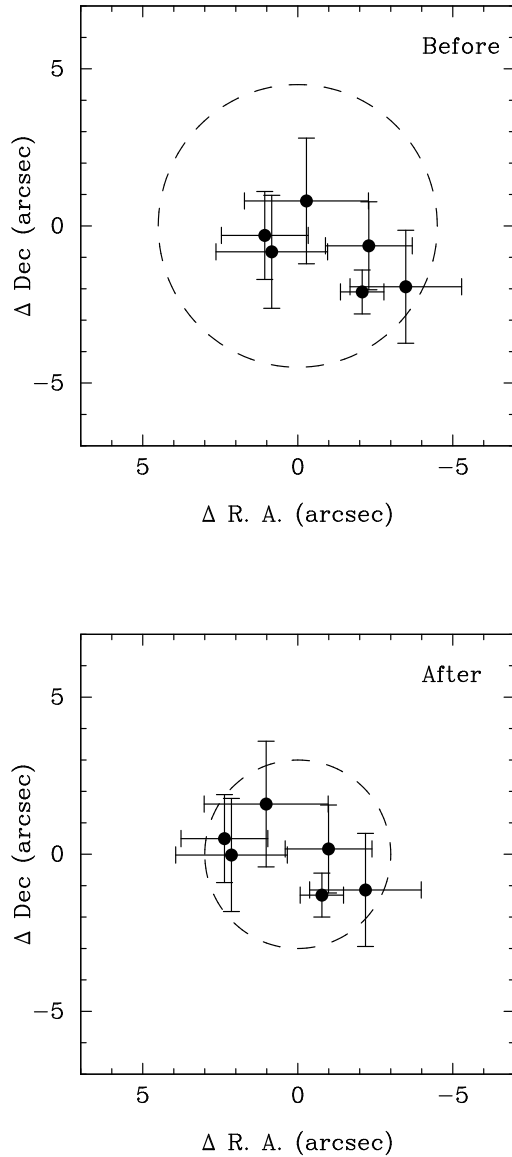


FIG. 3.— The result of using six optically identified, fainter HRI sources from Figure 2 to tie the X-ray positions to the optical astrometric reference frame. *Top*: The uncorrected position offsets. *Bottom*: The final offset between X-ray and optical position after applying a zero-point shift of $1''.3$ in right ascension and $0''.8$ in declination. Error bars are the 90% X-ray statistical uncertainties. We adopt a conservative radius of $3''$ for the uncertainty in position of RX J1836.2+5925.

use pulse-height channels 1–9, as there are virtually no X-ray photons in higher channels in the HRI. If we assume a constant source given by the count rate in the longer HRI observation, then we should expect to find in the source detection circle in 1995 a total of 24 photons (20 source and 4 background), whereas a total of only 12 were detected. The Poisson probability of obtaining 12 or fewer events when 24 are expected is 5.4×10^{-3} . Thus, the source is variable at the 99.5% confidence level. However, the existence of a *ROSAT* PSPC flux which is consistent with the latest HRI detection may be regarded as evidence contradictory to this indication of variability, and we would not be surprised if the one weak HRI detection turns out to be a statistical anomaly. Furthermore, the source *was* persis-

tent during the 1 month span of the HRI observation in which it was detected. The existence or not of variability is crucial to the detailed interpretation of the physics of this source, as we discuss below, but not to its identification with 3EG J1835+5918.

3. OPTICAL OBSERVATIONS OF RX J1836.2+5925

Armed with the precise X-ray position of RX J1836.2+5925, we reexamined the deepest optical images which we obtained on the MDM Observatory 2.4m telescope. Figure 4 is a reproduction of the V-band image from Paper 1, a total of 2 hr of exposure obtained on 2000 July 24. The adopted $3''$ radius error circle superposed. The circle is blank to a 3σ limit of $V > 25.2$. A limit of $R > 24.5$ was also obtained on 2000 July 15 (see Paper 1).

In order to guard against the possibility of an anomalous systematic error in the X-ray position, we obtained optical spectra of the three nearest objects to the west of the error circle on the Palomar 5m telescope. These objects are a late K star of magnitude $V = 20.7$, and two faint galaxies which show no evidence of activity in their optical spectra. They are therefore not viable candidates for identification with RX J1836.2+5925. We have also determined that no optical object in this field shows proper motion which could account for its positional discrepancy with the X-ray source. Thus, RX J1836.2+5925 remains undetected optically to a limit of $V > 25.2$, even allowing for a conservative uncertainty on its position. This upper limit implies that the ratio of X-ray-to-optical flux f_X/f_V is greater than 300, an extreme which is seen only among neutron stars.

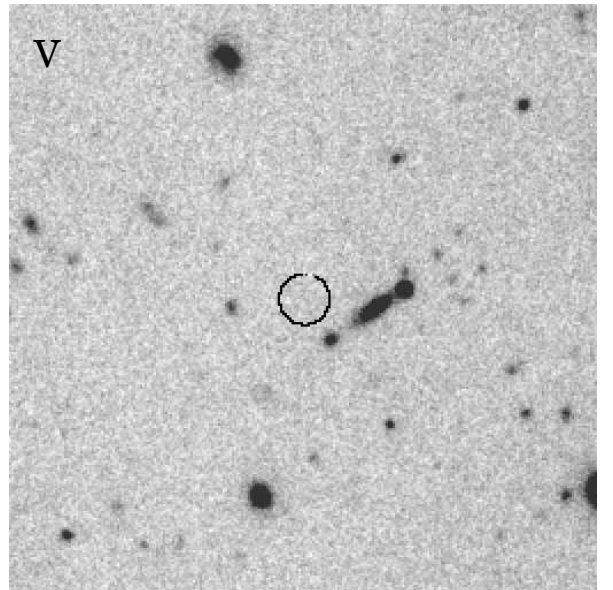


FIG. 4.— A deep V-band image at the location of the unidentified X-ray source RX J1836.2+5925. This 2 hr summed exposure from the MDM 2.4m telescope in seeing of $0''.8$ yielded a 3σ detection limit of $V = 25.2$. North is up, and east is to the left. The field is $70''$ across, and the *ROSAT* HRI error circle is drawn as a conservative $3''$ in radius as derived from Figure 3. The best position is (J2000) $18^h36^m13^s.77$, $+59^\circ25'30''.4$.

4. INTERPRETATION AND CONCLUSIONS

The latest analysis of the EGRET observations of 3EG J1835+5918 leads to the conclusion that it shows no evidence for long-term variability (Reimer et al. 2000). Its spectrum can be fitted by a relatively flat power law of photon index -1.7 from 70 MeV to 4 GeV, with a turn-down above 4 GeV. Such temporal and spectral behavior are more consistent with a rotation-powered pulsar than a blazar, which is the other major class of EGRET source. The soft X-ray source RX J1836.2+5925 located in the error box of the 3EG J1835+5918 presents properties that resemble a neutron star, and could be the second case of a nearby, radio-quiet γ -ray pulsar.

The detection of RX J1836.2+5925 in the *RASS* 7.5 yr prior to the final HRI observation eliminates an alternative hypothesis mentioned in Paper 1, that it might have been a luminous soft X-ray transient caused by the tidal disruption of a star by a supermassive black hole in a distant galaxy, and unrelated to 3EG J1835+5918. Such events are expected (and observed) to last only a few months (e.g., Komossa & Bade 1999; Komossa & Greiner 1999), while this source has persisted for at least 7.5 yr. Furthermore, our deep optical imaging failed to find a candidate galaxy at this location.

The available data from radio through γ -rays are thus consistent with the hypothesis that RX J1836.2+5925 is the actual counterpart of 3EG J1835+5918 and a more distant or older cousin of the Geminga pulsar. The implications of a neutron-star interpretation of RX J1836.2+5925 were discussed at length in Paper 1. Although the intrinsic flux of the source is highly uncertain because of the unknown column density, the latter is probably not greater than $3 \times 10^{20} \text{ cm}^{-2}$ or we would not be seeing such a soft spectrum. Then RX J1836.2+5925 is evidently at least 10–40 times fainter than Geminga. Thus it is either more distant than Geminga ($d > 160 \text{ pc}$, Caraveo et al. 1996), or cooler ($T < 5 \times 10^5 \text{ K}$, Halpern & Wang 1997). But a cooling neutron star of age $< 10^6 \text{ yr}$ should not be *too* distant, because to place it $> 400 \text{ pc}$ above the Galactic plane at $b = 25^\circ$ would require a kick velocity

at birth of $> 500 \text{ km s}^{-1}$. A reasonable upper limit on the distance is therefore 1 kpc, which we note implies an isotropic γ -ray luminosity of $6 \times 10^{34} (d/1 \text{ kpc})^2 \text{ ergs s}^{-1}$, rather more than the spin-down power $I\Omega\dot{\Omega}$ of Geminga ($3.3 \times 10^{34} \text{ ergs s}^{-1}$). If the actual spin-down power of 3EG J1835+5918 is determined, it will place an additional constraint on the distance and beaming factor.

The only observation that possibly complicates this interpretation is the marginally significant long-term (and non-monotonic) variability by about a factor of two. Such behavior is not consistent with surface thermal radiation of the heat of formation from the interior. However, it is possible that thermal emission from older neutron stars is dominated by the heated polar caps impacted by inflowing relativistic particles from the acceleration regions which are responsible for their pulsar action. Indeed, such reheating has been shown to be the source of the X-rays from the nearby recycled millisecond pulsar PSR J0437–4715 (Zavlin & Pavlov 1998). If under such conditions the particle acceleration regions in the pulsar were intermittent, the thermal X-rays resulting from this external heating would also be variable. In principle, 3EG J1835+5918 could be as powerful as Geminga at γ -ray energies, but less conspicuous at soft X-ray wavelengths because its surface has cooled except for the $\sim 1 \text{ km}$ radius polar caps which are being reheated directly by the accelerator. The most efficient γ -ray pulsars are expected to be the ones like Geminga, operating closest to their death lines (Chen & Ruderman 1993). A millisecond pulsar typically possesses spin-down power and magnetospheric gap voltage similar to Geminga and other ordinary pulsars. Since there is also evidence that the magnetospheric X-rays from Geminga are variable (Halpern & Wang 1997), either an exotic middle-aged pulsar or a maximally efficient recycled pulsar are plausible scenarios for 3EG J1835+5918.

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TABLE 1
X-RAY OBSERVATIONS OF RX J1836.2+5925/3EG J1835+5918

Instrument	Dates (UT)	Exposure Time (s)	Count Rate (s ⁻¹)
<i>ROSAT</i> PSPC ^a	1990 Oct 11–24	1532	$(1.46 \pm 0.41) \times 10^{-2}$
<i>ROSAT</i> HRI	1995 Feb 2–4	9078	$(0.90 \pm 0.51) \times 10^{-3}$
<i>ROSAT</i> HRI	1997 Dec 15 – 1998 Jan 20	60603	$(2.25 \pm 0.23) \times 10^{-3}$
<i>ASCA</i> GIS	1998 April 20–22	68900	. . .

^a The *ROSAT* All-Sky Survey

TABLE 2
RASS SPECTRUM OF RX J1836.2+5925

Energy bin (keV)	Counts
0.1–0.2	10.4 ± 5.8
0.2–0.3	11.9 ± 6.4
0.3–0.4	-0.5 ± 4.0
0.4–0.5	$+1.0 \pm 3.3$
0.5–2.0	-0.6 ± 5.3