A Deep Optical Observation for an Enigmatic Unidentified Gamma-Ray Source 3EG J1835+5918

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Abstract

We report a deep optical imaging observation by the Subaru telescope for a very soft X-ray source RX J1836.2+5925, which has been suspected to be an isolated neutron star associated with the brightest as-yet unidentified EGRET source outside the Galactic plane, 3EG J1835+5918. An extended source having a complex, bipolar shape is found at $B \sim 26$, and this might be an extended pulsar nebular whose flux is about 5-6 orders of magnitude lower than gamma-ray flux, although finding a galaxy of this magnitude by chance in the error circle is of order unity. We have found two even fainter, possibly point sources at $B \sim 28$, although their detections are not firm because of low signal-to-noise. If the extended object of $B \sim 26$ is a galaxy and not related to 3EG J1835+5918, a lower limit on X-ray/optical flux ratio is set as $f_X/f_B \gtrsim 2700$, giving a further strong support of the neutron-star identification of 3EG J1835+5918. Interestingly, if either of the two sources at $B \sim 28$ is the real counterpart of RX J1836.2+5925 and thermal emission from the surface of an isolated neutron star, the temperature and distance to the source become $\sim 4 \times 10^5 K$ and $\sim 300 pc$, respectively, showing a striking similarity of its spectral energy distribution to the proto-type radio-quiet gamma-ray pulsar Geminga. No detection of nonthermal hard X-ray emission is consistent with the ASCA upper limit, if the nonthermal flux of 3EG J1835+5918/RX J1836.2+5925 is at a similar level with that of Geminga.

Key words: gamma-rays: observations — stars: neutron
1. Introduction

Over half of GeV gamma-ray sources detected by the EGRET experiment have not yet been identified as known astronomical objects (Hartman et al. 1999), and understanding their origin is one of the most important issues in high-energy astrophysics. Many of unidentified sources located in the Galactic plane are believed to be associated with either of pulsars, supernova remnants, or massive stars as suggested by statistically significant correlation between unidentified EGRET sources and tracers of these objects (see, e.g., Romero 2001 for a review). Another Galactic population of unidentified EGRET sources at intermediate Galactic latitude ($|b| \lesssim 40^\circ$) has been reported by Gehrels et al. (2000), which are apparently associated with the Gould belt, and they might be off-beam gamma-ray pulsars (Harding & Zhang 2001). There are also unidentified sources at even higher latitude ($|b| \gtrsim 40^\circ$), suggesting the extragalactic origin. Variable sources among them are likely undetected blazars, while some stable sources might be dynamically forming or merging clusters of galaxies (Totani & Kitayama 2000; Waxman & Loeb 2000; Kawasaki & Totani 2002).

One of the unidentified EGRET sources, 3EG J1835+5918 has been paid particular attention in recent years, since it is the brightest unidentified source outside the Galactic plane ($l = 88.7^\circ$, $b = 25.1^\circ$). Its gamma-ray properties, i.e., steady flux and hard spectrum are consistent well with other gamma-ray pulsars observed by EGRET (Reimer et al. 2001), rather than blazars. No strong radio counterpart also argues against the blazar origin. Intensive multi-wavelength studies of this source (Mirabal et al. 2000; Mirabal & Halpern 2001; Reimer et al. 2001) have revealed about a dozen of X-ray sources in or around the error circle of 3EG J1835+5918, and most of them are coronal emission from stars or quasars without any special or blazar-like characteristics, which are not likely the counterpart of 3EG J1835+5918. Then the only one unidentified X-ray source, RX J1836.2+5925, remains as the most likely counterpart. It has very soft X-ray spectrum ($T < 5 \times 10^5$K) and has no optical counterpart down to $V \sim 25$ (Mirabal & Halpern 2001) giving a high X-ray/optical ratio. This and the lack of strong radio emission are reminiscent of the characteristics of isolated neutron stars or radio-quiet pulsars (e.g., Brazier & Johnston 1999; Neuhäuser & Trümper 1999), and this is why both Mirabal & Halpern (2001) and Reimer et al. (2001) concluded that the most likely identification of 3EG J1835+5918 / RX J1836.2+5925 is an isolated radio-quiet pulsar, which is similar to the proto-type object Geminga.

However, with the X-ray flux of $2-6 \times 10^{-13}$ erg cm$^{-2}$s$^{-1}$ (Mirabal & Halpern 2001), the optical upper limit ($V > 25.2$ at 3$\sigma$) corresponds to the X-ray/optical flux ratio of $f_X/f_V \gtrsim 300$, and it is not large enough compared with the flux ratio expected for isolated pulsars or neutron stars, although all X-ray sources other than isolated neutron stars and low-mass X-ray binaries have $f_X/f_V \lesssim 80$ (Stocke et al. 1991). Here we report a deep optical imaging observation of 3EG J1835+5918 / RX J1836.2+5925 by the 8.2m Subaru telescope, to examine the proposed
identification and the origin of this enigmatic source.

2. The Subaru Observation

The observation was made on July 17, 2001, by the Subaru/FOCAS whose field of view is a circle with 6′ diameter. We took images in $B$ and $U$ bands, with the total exposure time of 2400 and 6000 sec, respectively. The 5σ peak level corresponds to $B = 27.5$ and $U = 25.9$. Figures 1 and 2 show the $B$ band images centered on the position of RX J1836.2+5925 determined by Mirabal & Halpern (2001) with the error radius of 3″ (J2000, 18$^h$36$^m$13.77, +59°25′30″.4). The Galactic extinction to this direction is $A_B = 0.22$ and $A_U = 0.28$ (Schlegel, Finkbeiner, & Davis 1998) giving upper bounds on extinction in any Galactic objects. The seeing size in the $B$ band is 0.9′′ FWHM. On the other hand, the quality of $U$ band image is not as good as the $B$ band and no object is found in the error circle; we then set a rough upper limit of $U < 24.8$ including systematic uncertainty of photometry.

In the $B$ band image we detected two extended sources which are connected with each other (labeled as C and D in the images). Their peak are 5.1 and 5.8σ of the sky fluctuation level, respectively. We found two point-like sources with peak levels higher than 3σ levels, which are labeled as A and B in the images. The results of photometry as well as the source locations for the above four objects are summarized in Table 1. In the following of this paper, we will refer to the sources C and D as one source (C+D). We checked that the noise fluctuation is symmetric above and below the zero point of the background, and we did the same detection procedure for the inverted image to estimate the number of spurious objects. This indicates that sources A and B are not firm detections; the probabilities that they are spurious detection are estimated to be ∼ 60 and 30%, respectively, from the counts of spurious objects in the inverted frame. An even fainter, extended source can be seen in the bottom of the error circle, whose peak level is less than 3σ, and we do not consider this source in this letter.

If 3EG J1835+5918 is a pulsar with high proper motion, it might have moved to outside of the error circle determined by ROSAT data. Therefore examination only within the ROSAT error circle is not sufficient. Our observation is 3.5yr later than the ROSAT HRI observation (Mirabal & Halpern 2001), and assuming a distance of 200pc and transverse velocity of 500km/s, the proper motion becomes ∼2″. Therefore we examined the outer region 2″ beyond the ROSAT error circle, but we found no significant sources like A–D.

3. Implications and Discussion

First we consider the possibility that C+D is an interacting galaxy. The $B$-band galaxy count at $B \sim 26$ is about $2 \times 10^5$ mag$^{-1}$deg$^{-2}$ (e.g., Totani & Yoshii 2000), and hence the number of galaxies expected in the error circle of RX J1836.2+5925 becomes ∼0.4, indicating that the appearance of a galaxy by chance is not surprising at all. The X-ray spectrum of
RX J1836.2+5925 is very soft, and this argues against the possibility that the X-ray emission is coming from nuclear activity in extended faint galaxies. As mentioned earlier, the gamma-ray properties and lack of strong radio emission also disfavor the AGN origin for 3EG J1835+5918. The morphology of C and D suggests that they are merging or interacting galaxies, and steady radiation of gamma-rays may be possible by particle acceleration from merging shocks. However, assuming typical values of mass/light ratio of galaxies, merging velocity (~ a few hundreds km/s), and interaction time scale (~ $10^8$ yr), we estimated the maximum luminosity possible from merging, as the merging kinetic energy divided by the interaction time scale. It turns out to be of order $\sim 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, and this is more than four orders of magnitude weaker than the gamma-ray flux of 3EG J1835+5918, safely excluding this possibility. Therefore, if the source C+D is a galaxy, it is not a counterpart of 3EG J1835+5918.

Another possibility which should be considered here is that the extended object C+D is a pulsar wind nebula. The optical $\nu F_\nu$ flux is more than 5 orders of magnitude lower than the gamma-ray flux, and hence than the spin-down luminosity of the pulsar. The size of the extended objects, ~ 1", seems small as an entire size of typical synchrotron nebulae, but observations of other pulsars or pulsar candidates have often revealed extended cores or knots with similar size around central pulsars, e.g., optical knots in the Crab pulsar (Hester et al. 1995) or Chandra observations of several Crab-like young supernova remnants (Slane et al. 2000; Hughes et al. 2001). Nonthermal X-ray synchrotron nebula emission is known to be correlated to the spin-down luminosity as $L_X \sim 10^{-2} \dot{E}$ (e.g., Seward & Wang 1988; Becker & Trümper 1997), and the compact (but extended) X-ray cores have a flux of about 10% of the total nebula flux (Slane et al. 2000; Hughes et al. 2001). The optical flux of the object C+D seems small compared with these X-ray fluxes. On the other hand, the optical knots of the Crab pulsar have luminosity about seven orders of magnitude lower than the spin-down luminosity, and hence the object C+D may be a similar knot embedded in a nebula which is much more extended and undetected. Since the object is located at intermediate Galactic latitude ($b = 25.2^\circ$), the pulsar is likely to have a high velocity. Then it is possible that the extended nebular is a bow shock where the ram pressure from interstellar matter and the pulsar wind pressure are in equilibrium:

$$nm_p \upsilon^2 = \frac{\dot{E}}{4\pi r_s^2 c} = \frac{f^{-1}_\gamma (4\pi D^2 F_\gamma)}{4\pi r_s^2 c} = \frac{f^{-1}_\gamma F_\gamma}{c \theta_s^2},$$

where $\dot{E}$ is the spin-down luminosity assumed to be the same as the wind luminosity, $n$ the nucleon density of ambient medium, $m_p$ the proton mass, $\upsilon$ the pulsar velocity, $D$ the distance to the pulsar, $f_\gamma$ the ratio of gamma-ray luminosity to spin-down luminosity, $F_\gamma$ the observed gamma-ray flux ($= 3.4 \times 10^{-10}$ erg cm$^{-2}$ s$^{-1}$), $r_s$ the radius of the bow shock, and $\theta_s = r_s/D$. This equation suggests a reasonable density of ambient matter as

$$n = 1.8 \left( \frac{f_\gamma}{0.1} \right)^{-1} \left( \frac{\theta_s}{1''} \right)^{-2} \left( \frac{\upsilon}{400 \text{ km/s}} \right)^{-2} \text{ cm}^{-3},$$

where $\theta_s = r_s/D$. The proton mass $m_p$ is $1.67 \times 10^{-24}$ g, and the proton velocity $\upsilon$ is $400$ km/s. The proton mass $m_p$ is $1.67 \times 10^{-24}$ g, and the proton velocity $\upsilon$ is $400$ km/s.
although it might be higher than expected for the mid Galactic latitude region. We must await further multi-band optical observation to clarify whether the extended object is a galaxy or a synchrotron nebula.

In the following we assume that C+D is not related to RX J1836.2+5925/3EG J1835+5918. The flux of possible point sources A and B sets an upper limit of $B \gtrsim 28$ for point sources, which is much stronger than previous limit of $V > 25.2$. This translates to the lower limit of $f_X/f_B \gtrsim 2700$ on RX J1836.2+5925. If we assume the Reyleigh-Jeans spectrum ($B-V = -0.32$) as expected for thermal emission from an isolated neutron star, the limit on the X-ray/$V$ ratio becomes $f_X/f_V > 5300$. (However, it should also be noted that the optical spectrum of isolated neutron stars is often not entirely the black-body, as is the case for the Geminga.) This limit on X-ray/optical flux ratio further strengthens the argument for the isolated neutron-star identification for RX J1836.2+5925. Star counts in such a faint magnitude are not well constrained, but a typical theoretical model predicts about 10000–15000 stars per square degree down to $B \sim 28$ to the direction of RX J1836.2+5925, with an extreme assumption that ancient white dwarfs contribute 100% of the dark halo of our Galaxy (Robin, Reylé, & Créze 2000; A. Robin, private communication). Then the expected star count in the 3′-radius error circle is about 0.03 stars, and hence a random coincidence of a star in the error circle of RX J1836.2+5925 seems to be unlikely. On the other hand, we cannot reject a possibility that the point-like objects A and/or B are small galaxies which could not be resolved. Keeping these caveats in mind, we assume that one of the two is a real isolated pulsar and the physical counterpart of RX J1836.2+5925, and then discuss implications in this case.

To examine the physical connection between RX J1836.2+5925 and 3EG J1835+5918, we should also estimate the chance probability of finding an isolated neutron star within the error circle of 3EG J1835+5918 (12′ radius). Based on the estimations of pulsar birth rate (e.g., Narayan & Ostriker 1990) and supernova rate (e.g., Totani, Sato, & Yoshii 1996), about $10^{8–9}$ neutron stars are typically expected to exist in our Galaxy. Thermal emission can be observed by either cooling neutron star surfaces or those heated by accretion of interstellar matters. Neuhäuser & Trümper (1999) compiled observational constraints on the X-ray counts of such neutron stars detectable by the ROSAT all sky survey, and compared them with theoretical expectations. Since neutron stars rapidly cool down after $\sim 10^6$yr according to the standard cooling theory of neutron stars (Friedman & Pandharipande 1981), the expected count of cooling neutron stars is much smaller than that of the accreting neutron stars. The former is $\sim 1–10$ sr$^{-1}$ for ROSAT X-ray flux of $\gtrsim 10^{-13}$ erg cm$^{-2}$s$^{-1}$, and the expected number in the 12′-radius error circle of 3EG J1835+5918 is found to be sufficiently small as $\sim (4–40) \times 10^{-5}$. The estimate for accreting neutron stars is rather uncertain and it could be much higher than that for cooling neutron stars, but the observational upper bound by ROSAT is $\lesssim 100–1000$ sr$^{-1}$ again at $f_X \gtrsim 10^{-13}$ erg cm$^{-2}$s$^{-1}$, and the expected count in the EGRET error circle should be less than $\sim 0.04$. It should also be noted that 3EG J1835+5918 is at intermediate
Galactic latitude. Then it seems unlikely that it is heated by accretion, since the ambient gas density should not be high and the neutron star should have high-velocity proper motion. (The Bondi-Hoyle accretion rate scales as $\propto v^{-3}$.)

Now we discuss the broad-band spectral energy distribution of this source, assuming that 3EG J1835+5918 and RX J1836.2+5925 are physically associated and it is a gamma-ray pulsar. Assuming the thermal flux of $B \sim 28$ from the neutron star surface, we can derive thermal temperature and distance, by scaling from the proto-type gamma-ray pulsar Geminga. The thermal X-ray spectrum of Geminga can be fitted with $T = 5.6 \times 10^5 K$ (Halpern & Wang 1997), and its optical $B$-band flux ($B = 26.3$, Mignani, Caraveo, & Bignami 1998) is about a factor of 5.8 higher than the extrapolation from the X-ray flux. Such a trend, i.e., optical flux that is a factor of several higher than that extrapolated from X-ray temperature, has been known also for another isolated neutron star, RX J185635−3754 (Walter & Matthews 1997). Assuming this factor also for RX J1836.2+5925, we obtain the black-body temperature of $T = 4.1 \times 10^5 K$ from the X-ray/optical flux ratio, assuming $N_H = 1 \times 10^{20}$ cm$^{-2}$. If the effective emission area of thermal radiation is the same, the optical flux in the Rayleigh-Jeans region scales as $f \propto T/D^2$. Therefore, the distance to RX J1836.2+5925 can be inferred as $D \sim 300$pc, from the known distance of Geminga ($\sim 160$pc, Caraveo et al. 1996). The inferred black-body spectrum of RX J1836.2+5925/3EG J1835+5918 is shown in terms of absolute $\nu L_\nu$ luminosity by the solid line in Fig. and the observed gamma-ray, X-ray and optical luminosities or upper limits are also shown by open circles or solid lines. The error bar of the soft X-ray data point (0.2keV) is showing the flux change when different column densities of $N_H = 0$ or $3 \times 10^{20}$ cm$^{-2}$ are assumed, with the same temperature. The upper bound on hard X-ray flux (>1keV) is from ASCA observation (Mirabal et al. 2000). For comparison, the black-body spectrum and observed luminosities of Geminga in optical, soft and hard X-ray, and gamma-ray bands are shown by dashed lines or crosses. A striking similarity of the spectral energy distribution between Geminga and RX J1836.2+5925/3EG J1835+5918 can be seen. The no detection of nonthermal X-rays from RX J1836.2+5925 is marginally consistent with the ASCA upper bound, if the nonthermal X-ray luminosity is similar to that of Geminga. Assuming the distance of 300pc and an age of the pulsar to be $\sim 3 \times 10^5$yr, which is similar to that of Geminga, the Galactic latitude of $b = 25^\circ$ implies a reasonable transverse proper motion of $\sim 300(t_{age}/3 \times 10^5$yr)$^{-1}$ km/s.

To summarize, we found an extended source having a peculiar shape (C+D) at $B \sim 26$ within the error circle of RX J1836.2+5925, which has been suspected as an isolated pulsar associated with 3EG J1835+5918. This source might be a pulsar nebular or knot whose luminosity is about 5–6 orders of magnitude lower than the gamma-ray luminosity. However, it is statistically well possible that a galaxy appeared by chance as the source C+D within the

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1 From the X-ray temperature and bolometric thermal flux of the Geminga pulsar (Halpern & Wang 1997), the distance of 160pc corresponds to the blackbody radius of $R_\infty \equiv R/[(1 - (2GM/Rc^2))^{1/2} = 4.6km$. 

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Table 1. Result of Observation around RX J1836.2+5925

| object | profile | α(J2000)   | δ(J2000)   | B mag   |
|--------|---------|------------|------------|---------|
| A      | point   | 18h36m13.49s | 59d25m30.1s | 29.1_{-0.7}^{+1.9} |
| B      | point   | 18h36m13.90s | 59d25m29.1s | 28.3_{-0.4}^{+0.6} |
| C      | extended| 18h36m13.87s | 59d25m31.6s |         |
| D      | extended| 18h36m13.93s | 59d25m32.0s |         |
| C+D    |         |             |            | 26.1±0.1 |

examined error circle. There are two fainter possible point sources (A, B) at $B \sim 28$, although they are not firm detections because of low signal-to-noise. It is interesting that if either of A or B is a real counterpart of RX J1836.2+5925 and thermal emission from a neutron star, its optical, X, and gamma-ray luminosities are very similar to those of the prototype gamma-ray pulsar Geminga. The pulsar identification of Geminga came from the detection of pulsation in X-ray flux, and hence it can be imagined that the ultimate identification of the enigmatic source 3EG J1835+5918 will also be brought by discovery of X-ray pulsation. On the other hand, further deep optical study is also very important to verify whether the extended source C+D is a galaxy or not, to confirm the possible point sources A and/or B with higher signal-to-noise ratio, and to measure proper motion and parallax for distance determination.

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Fig. 1. The $30'' \times 30''$ image in the $B$ band around the region of RX J1836.2+5925 whose error circle is shown by the circle. The four objects found in the circle are indicated as A–D. North is up.

Fig. 2. The same as Fig. 1, but a close-up of the $10'' \times 10''$ region centered on RX J1836.2+5925.
Fig. 3. Spectral energy distribution of RX J1836.2+5925/3EG J1835+5918 (solid lines and open circles) and Geminga (dashed lines and crosses), in optical, X-ray and gamma-ray bands. Distances are assumed to be 300pc for RX J1836.2+5925/3EG J1835+5918 while the known distance of 160pc is used for Geminga. The black-body temperature is 4.1 and $5.6 \times 10^5$K for the former and the latter, respectively. The optical flux of RX J1836.2+5925/3EG J1835+5918 is $B = 28.0$, assuming that the source A or B is the real counterpart of this object. In the hard X-ray band (>1keV), the upper limit from ASCA is shown for RX J1836.2+5925 (solid line), while the two fits to the ASCA SIS or GIS by Halpern & Wang (1997) are shown for Geminga (dashed line).