TO APPEAR IN *The Astrophysical Journal Letters*
Preprint typeset using LaTeX style emulateapj v. 14/09/00

THE NEXT GEMINGA: DEEP MULTIWAVELENGTH OBSERVATIONS OF A NEUTRON STAR IDENTIFIED WITH 3EG J1835+5918

J. P. HALPERN, E. V. GOTTHELF, N. MIRABAL, AND F. CAMILO
Columbia Astrophysics Laboratory, Columbia University, 550 West 120th Street, New York, NY 10027

To appear in The Astrophysical Journal Letters

ABSTRACT

We describe *Chandra*, *HST*, and radio observations that reveal a radio-quiet but magnetospherically active neutron star in the error circle of the high-energy γ-ray source 3EG J1835+5918, the brightest of the unidentified EGRET sources at high Galactic latitude. A *Chandra* ACIS-S spectrum of the ultrasoft X-ray source RX J1836.2+5925, suggested by Mirabal & Halpern as the neutron star counterpart of 3EG J1835+5918, requires two components: a blackbody of $T_\infty \approx 3 \times 10^5$ K and a hard tail that can be parameterized as a power law of photon index $\Gamma \approx 2$. An upper limit of $d < 800$ pc can be derived from the blackbody fit under an assumption of $R_\infty = 10$ km. Deep optical imaging with the *HST* STIS CCD failed to detect this source to a limit of $V > 28.5$, thus $f_X/f_V > 6000$ and $d > 250$ pc assuming the X-ray fitted temperature for the full surface. Repeated observations with the 76 m Lovell telescope at Jodrell Bank place an upper limit of < 0.1 mJy on the flux density at 1400 MHz for a pulsar with $P > 0.1$ s, and < 0.25 mJy for a ~ 10 ms pulsar at the location of RX J1836.2+5925. All of this evidence points to an older, possibly more distant version of the highly efficient γ-ray pulsar Geminga, as the origin of the γ-rays from 3EG J1835+5918.

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 a puzzle 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., Halpern & Ruderman 1993; Helfand 1994; Kaaret & Cottam 1996; Yadigaroglu & Romani 1997), and that many of them are radio quiet. That Geminga is a bright EGRET source at a distance of only ~ 200 pc (Halpern & Ruderman 1993; Caraveo et al. 1996) begs for it not to be unique.

As a γ-ray pulsar spins down, an increasing fraction of its power is emitted above 100 MeV (Thompson et al. 1997, 1999). This implies that the γ-ray source population is not necessarily dominated by *young* pulsars. Like Geminga and PSR B1055–52, many of them could be quite old, up to 10^6 yr or more. Geminga itself has a characteristic age of 3.4×10^5 yr, and the EGRET pulsar PSR B1055–52 is $\approx 5 \times 10^5$ yr old. The unidentified γ-ray sources may therefore include a significant fraction of the nearby neutron-star population that has yet to be accounted for, and may provide a useful window into their physics. It is also speculated (Gehrels et al. 2000; Grenier 2000; Harding & Zhang 2001) that as many as 40 of the steady, unidentified EGRET sources at intermediate Galactic latitude are a population of older pulsars born in the Gould Belt, an inclined, expanding disk of star formation in the solar neighborhood that is $\approx 3 \times 10^7$ yr old. If so, they will most easily be identified as soft blackbody X-ray sources without optical counterparts.

As the brightest of the as-yet unidentified high-latitude EGRET sources (Hartman et al. 1999), at $(\ell, b) = (89^\circ, +25^\circ)$, 3EG J1835+5918 is a good a priori target for the next such identification, and a candidate for the prototype of the putative Gould Belt pulsars. Mirabal et al. (2000, hereafter Paper I) performed an exhaustive, multiwavelength search for a counterpart of 3EG J1835+5918. They identified optically all but one of the *ROSAT* and *ASCA* sources in the region of 3EG J1835+5918 to a flux limit of $\sim 5 \times 10^{-14}$ ergs cm^{-2} s^{-1}, which is 10^{-4} of the γ-ray flux, without finding a plausible counterpart among the identified sources. Mirabal & Halpern (2001, hereafter Paper II) concluded that the one optically undetected X-ray source, RX J1836.2+5925 (also the brightest one in the EGRET error circle), is the most promising candidate for identification with 3EG J1835+5918 principally because of the absence of optical emission. The upper limit (at that time) on the optical flux from RX J1836.2+5925 implied that its ratio of X-ray-to-optical flux f_X/f_V is greater than 300, an extreme that is seen only among neutron stars. The detection of RX J1836.2+5925 as a weak, ultrasoft source in the *ROSAT* All-Sky Survey (Paper II), further suggested that it is a thermally emitting neutron star that is either older or more distant than Geminga.

We designed follow-up observations with the *Chandra X-ray Observatory* and the *Hubble Space Telescope* (*HST*) to test this hypothesis and to further characterize the properties of the presumed neutron star. We also re-examined its location for evidence of a radio pulsar. Previous searches of the 3EG J1835+5918 error box failed to find a radio pulsar to a limit of 1 mJy at 770 MHz (Nice & Sayer 1997), and radio continuum observations of the entire error box using the VLA at 1420 MHz yielded an upper limit of 0.5 mJy at the location of RX J1836.2+5925 (Paper I). These limits are not below the range of several radio pulsar detections, so we performed deeper searches at Jodrell Bank to improve upon them.

2. CHANDRA X-RAY OBSERVATION

A *Chandra* observation with the Advanced CCD Imaging Spectrometer (ACIS; Burke et al. 1997) was made on 2002 March 6. The target source RX J1836.2+5925 was positioned at the default position on the back-illuminated S3 chip of the ACIS-S array. The total usable exposure time was 28,117 s. Figure 1 shows a smoothed version of the image. A total of

260 counts were extracted from a 1.″9 radius circle centered on RX J1836.2+5925 using the CIAO "psextract" script. A spectral file was produced by grouping at least 20 counts per channel. Instrument and mirror response files were generated using the CIAO tools "makermf" and "makearf". The expected contribution of background to the source spectrum is only ≈ 4 counts, so no background subtraction was performed. There is no evidence for extended emission (synchrotron nebulosity) associated with this source.

Figure 2 shows the grouped ACIS spectrum, which is clearly that of an ultrasoft source, as first revealed by the *ROSAT* All-Sky Survey (Paper II). The fact that the counts are rising down to the lowest energy signifies both a soft intrinsic spectrum and little absorbing column. Although the ACIS response below 0.6 keV may not be well calibrated (e.g., Zavlin et al. 2002), we do not have the freedom to exclude these energies from spectral fitting because they contain the majority of our photons. Instead, we proceed with the following analysis based on the current calibration. First, we ignore the spectral channel around 0.28 keV, since a deviant point there may be associated with poor instrumental calibration around the carbon K-edge. Next, attempts to fit the spectrum using a blackbody or power-law model alone produced unsatisfactory fits, with χ^2/dof = 10 and 4, respectively. This result is insensitive to $N_{\rm H}$, whether the latter is treated as a free parameter or held fixed at the maximum Galactic value in this direction (4.6×10^{20} cm^{-2}). A two-component model consisting of a blackbody plus a power law produced adequate fits, with reduced $\chi^2 < 1.4$ for all values of $N_{\rm H} \leq 4.6 \times 10^{20}$ cm^{-2}. However, the small number of photons, extremely soft spectrum, and unknown intervening column density render the blackbody flux and bolometric luminosity highly uncertain even if the instrument response were known accurately. Rather than leaving $N_{\rm H}$ a free parameter in the fits, we explore the effects of assuming particular values of $N_{\rm H}$ ranging from 2.5×10^{19} cm^{-2} to the maximum Galactic value of 4.6×10^{20} cm^{-2}. Figure 3 shows the corresponding confidence contours. The best fitted blackbody temperatures for this range of $N_{\rm H}$ vary from $(2.9-3.5) \times 10^5$ K, with a 1σ upper limit of 5.5×10^5 K. The high-energy tail that is required to accompany the blackbody component is parameterized as a power-law of photon index $1.6 \leq \Gamma \leq 2.8$ (1σ limits), with flux in the $0.2-2.0$ keV band of $(1.9-2.6) \times 10^{-14}$ ergs cm^{-2} s^{-1}.

We bound the range of plausible distances by assuming a blackbody radius of 10 km for each of the trial values of $N_{\rm H}$. Under this assumption, $100 \leq d \leq 800$ pc, and $5 \times 10^{30} \leq L_{\rm Bol} \leq 1.1 \times 10^{31}$ ergs s^{-1}; smaller distance corresponds to smaller temperature. Formally, no lower limit on T_∞ can be set from the X-ray spectrum alone, although the distance would become unreasonably small for $T_\infty < 3 \times 10^5$ K given the lack of optical detection, which sets an additional lower bound on d (see §3).

Precise astrometry of the ACIS image in the USNO-A2.0 optical reference frame was achieved by registration of four previously identified, "bright" X-ray sources in Figure 1 with their optical counterparts on the MDM 2.4m V-band CCD image described in Papers I and II. This required a zero-point shift to the *Chandra* aspect solution of –0.″13 in right ascension and –0.″39 in declination, which is within specifications. The corrected position of RX J1836.2+5925 is (J2000) $18^{\rm h}36^{\rm m}13.^{\rm s}723, +59^\circ 25' 30.''05$, which should be accurate to 0.″1 relative to our ground-based optical image as indicated by the residual dispersion in X-ray-optical offsets of the identified sources. We note that this position is only 0.″5 from the *ROSAT* HRI position that was determined in a similar manner in Paper II, confirming that the latter's error circle radius of 3″ was conservative. The agreement in position between these two X-ray observations that were made 4 years apart already limits any proper motion of the source to $< 1''$ yr^{-1}.

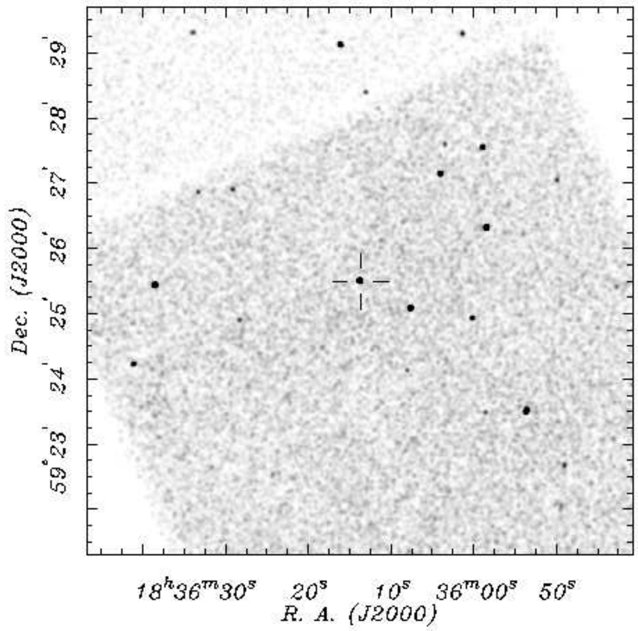

FIG. 1.— Smoothed *Chandra* ACIS-S3 image centered on the source RX J1836.2+5925 (*cross*).

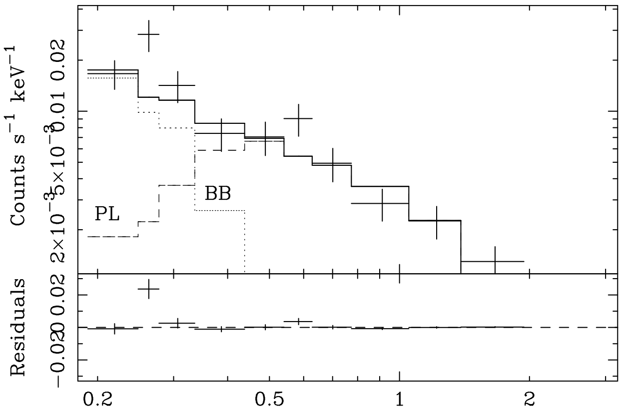

FIG. 2.— *Chandra* ACIS-S3 spectrum of RX J1836.2+5925, the neutron star counterpart of 3EG J1835+5918. *Top panel*: Data (*crosses*) and best-fit model (*thick line*) for an assumed $N_{\rm H} = 4.6 \times 10^{20}$ cm^{-2} (see text). Contributions of the blackbody (*dotted line*) and power law (*dashed line*) components are shown. *Bottom panel*: Difference between data and model, in the same units as the top panel.

3. HST STIS CCD IMAGING

Deep images were obtained on 2002 February 2 using the *Space Telescope Imaging Spectrograph* (STIS) CCD on *HST*, both with open filter (50CCD) and long-pass filter (F28X50LP). In each filter, a total exposure time of 10,400 s was obtained in a standard parallelogram dither pattern with four exposures at

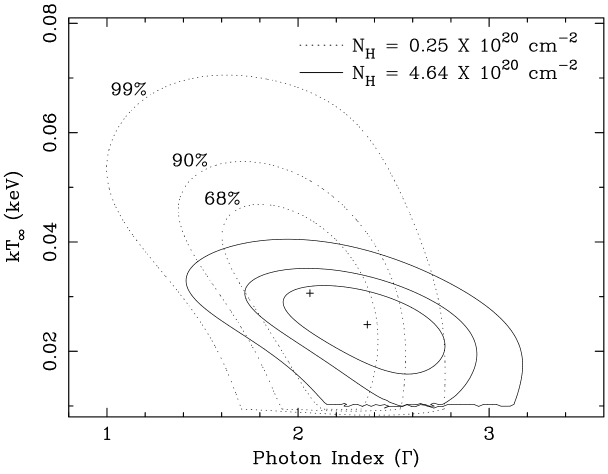

FIG. 3.— Confidence contours for the two-component fit (kT_∞, Γ) to the *Chandra* spectrum of RX J1836.2+5925. The intervening column density has been held fixed at two different values, the maximum Galactic value being $N_{\rm H} = 4.6 \times 10^{20}$ cm^{-2}. Confidence levels are for two interesting parameters.

each point to facilitate the rejection of cosmic rays. The data were processed using the standard STIS pipeline, registered, and combined according to the dither pattern. Figure 4 shows a portion of the resulting open filter image centered on RX J1836.2+5925. Aperture photometry was used to obtain STIS magnitudes from the PHOTLAM and PHOTZPT keywords in the image headers. We then adopted the transformation equations derived by Rejkuba et al. (2000) from observations of stars in the irregular galaxy WLM to convert STIS magnitudes in the open and long-pass filters to the V and I Kron-Cousins system. We also examined a set of objects in the STIS images that we had previously calibrated in ground-based photometry, and the zero-points agree. Thus, we find that the limiting magnitudes for point-source detection at the 3σ level are $V = 28.8$ from the 50CCD image and and $I = 26.5$ from the F28X50LP. The main uncertainty in this calibration is due to the broad passbands of the STIS filters, and is estimated as 0.2 mag.

In order to tie the *HST* and *Chandra* images to the same astrometric reference frame, we used the positions of 10 objects that are present on the both the *HST* STIS and ground-based CCD images to transfer the USNO-A2.0 reference frame to the STIS image. These objects include stars and compact galaxies. The dispersion among these 10 secondary astrometric standards from the fit to their *HST* positions is $0\farcs065$, or slightly larger than 1 STIS pixel. Thus, the combined uncertainty in *Chandra* and *HST* astrometry is less than $0\farcs2$; we use a conservative error circle of radius $0\farcs2$ in Figure 4 to indicate the location of the X-ray source on the STIS image. Since the *HST* and *Chandra* observations were made only one month apart, we are confident that any proper motion, already limited to $< 1''$ yr^{-1}, is of no importance.

The *Chandra* error circle excludes all of the optical objects within the *ROSAT* error circle that were detected by Totani, Kawasaki, & Kawai (2002) in their B-band image obtained on the Subaru telescope. At the northeast edge of the *Chandra* error circle there is only a marginal source of $V \approx 29.0 \pm 0.4$ in the STIS 50CCD image, but it is not present in the F28X50LP image. Since this is not even a 3σ detection, we consider that the X-ray source is formally undetected optically, with upper limits of $V > 28.5$ and $I > 26.5$, and that it must therefore be a neutron star with $f_X/f_V > 6000$. The absence of an optical detection places additional constraints on the distance and temperature of the neutron star RX J1836.2+5925. A magnitude limit of $V > 28.5$ corresponds to a flux $< 0.014\,\mu$Jy at a wavelength of 5500 Å, whereas the Rayleigh-Jeans flux from a neutron star at that wavelength would be $0.030\,T_5\,(R_{10}/d_{100})^2\,\mu$Jy, where T_5 is T_∞ in units of 10^5 K, R_{10} is the radius in units of 10 km, and d_{100} is the distance in units of 100 pc. Therefore, the nominal X-ray fitted temperature of 3×10^5 K, if coming from the full surface of the neutron star, would require $d > 250$ pc.

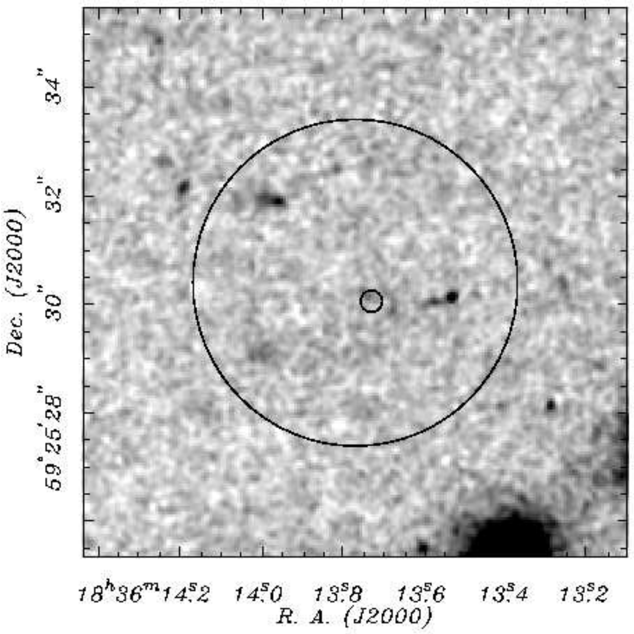

FIG. 4.— Smoothed, open filter *HST* STIS image centered on the X-ray source RX J1836.2+5925. The $3''$ radius error circle from the *ROSAT* HRI, and the $0\farcs2$ radius *Chandra* error circle are shown. The limiting magnitude of this image is equivalent to $V = 28.8$.

4. RADIO PULSAR SEARCH

The absence of a "strong," i.e, ~ 0.5 mJy radio source at the position of RX J1836.2+5925 was already known from Paper I. In order to make a more sensitive search for radio pulsations, we obtained six observations on different days in 2001 February and March for 2.3 hr each with the Jodrell Bank 76 m Lovell telescope at a frequency of 1400 MHz. A 64×1 MHz filter bank and a sampling time of 1 ms were used. Since the maximum expected dispersion measure is small at this high-latitude location, DM ≤ 17 pc cm^{-3} for $d \leq 1$ kpc according to the Taylor & Cordes (1993) model, the limiting flux density for pulsations is insensitive to distance or period in the range $P > 100$ ms, being 0.1 mJy for a duty cycle of 10%. A period in this range is expected for an older, Geminga-like pulsar. For $P < 100$ ms, the sensitivity diminishes rapidly, to ≈ 0.25 mJy at 10 ms. Scintillation might be expected for these DM values and observing parameters, but our six observations should adequately sample most any such variability. Finally, we obtained a single 9.3 hr pointing on 2002 February 18 with the same sampling as before, which reduces the nominal sensitivity to $50\,\mu$Jy, although scintillation may play a role here. No pulsations were detected in any observation.

Adopting an upper limit of 800 pc to the distance from the blackbody fit to the X-ray spectrum, a conservative upper limit on the pulsed radio luminosity of RX J1836.2+5925 is $L_{1400} < 0.064$ mJy kpc^2. The least luminous young pulsar known in radio is the one in the supernova remnant 3C 58, with $L_{1400} \approx 0.5$ mJy kpc^2 (Camilo et al. 2002a), and there are only four pulsars known with $L_{1400} < 0.1$ mJy kpc^2 (Camilo et al. 2002b) in addition to Geminga (McLaughlin et al. 1999, and references therein). RX J1836.2+5925 is certainly in contention as a radio-quiet pulsar, although it would not be surprising if more sensitive observations discover it at slightly lower flux density than explored here.

5. DISCUSSION AND CONCLUSIONS

The results of these deep X-ray, optical, and radio observations are quite revealing of the properties of RX J1836.2+5925. Without exception they support the hypothesis that it is an older and possibly more distant cousin of the Geminga pulsar, and readily identifiable with the EGRET source 3EG J1835+5918 in which error circle it lies. First, the X-ray source, which is primarily an ultrasoft blackbody of $T_\infty \approx 3 \times 10^5$ K, is significantly cooler than the oldest "ordinary" γ-ray pulsars Geminga and PSR B1055–52, which have $T_\infty = (5.6 \pm 0.6) \times 10^5$ K and $(7.5 \pm 0.6) \times 10^5$ K, respectively (Halpern & Wang 1997; Ögelman & Finley 1993). Most of the neutron star cooling curves that match the temperatures of Geminga and PSR B1055–52 drop to $T_\infty = 3 \times 10^5$ K at an age $\geq 1 \times 10^6$ yr (e.g., Yakovlev et al. 2002), approximately 3 times the characteristic age of Geminga. At the same time, the difference in temperature is not sufficient to account for the factor of 40 difference in soft X-ray flux between Geminga and RX J1836.2+5925, so the latter may be as far away as 800 pc, as compared to $d \sim 200$ pc for Geminga. At the maximum distance, RX J1836.2+5925 would be 340 pc from the Galactic plane, not an unreasonable distance for a neutron star to have traveled in 10^6 yr (Paper II).

Even more important is the presence of an apparently nonthermal extension to the X-ray spectrum. All of the EGRET pulsars, even the oldest ones, have such "power-law" components that can be explained in terms of synchrotron emission from secondary particles that are produced in the conversion of primary γ-rays in the strong magnetic field near the surface of the neutron star (Wang et al. 1998). No γ-ray pulsar lacks such a nonthermal X-ray spectrum, while several middle-aged or older pulsars that might be expected to be EGRET sources based on their proximity and/or spin-down power have only thermal X-ray spectra and no γ-ray emission. That a neutron star as cool as RX J1836.2+5925 possesses a non-thermal X-ray tail is encouraging of a connection with 3EG J1835+5918.

All of the non-thermal manifestations of 3EG J1835+5918 are fainter than the corresponding emission from Geminga: by a factor of ≥ 20 in the optical, ≈ 15 in the X-ray, and ≈ 6 in the γ-ray. Its thermal X-ray flux, although difficult to quantify, is also much less than that of Geminga. While RX J1836.2+5925 is relatively inconspicuous, it *is* the brightest soft X-ray source within the error circle of 3EG J1835+5918. If a fainter X-ray source were considered as a possible counterpart, it would only exacerbate the differences between this and other, identified EGRET sources as discussed in Paper I.

Finally, we mention once again the two pieces of evidence that suggest 3EG J1835+5918 itself is a priori more likely to be a pulsar rather than, e.g., a blazar, the other major class of EGRET source. According to Reimer et al. (2001) it shows no evidence for long-term variability, and its spectrum can be fitted by a relatively flat power law of $\Gamma = 1.7$ from 70 MeV to 4 GeV, with a turn-down above 4 GeV. In contrast, blazars are highly variable, and tend to have steeper spectra. The energetics of 3EG J1835+5918 are also plausible for a pulsar at $d < 800$ pc since its γ-ray luminosity (assumed isotropic) is $3.8 \times 10^{34}\,(d/800\,\mathrm{pc})^2$ ergs s^{-1}, comparable to the spin-down power $I\Omega\dot{\Omega}$ of Geminga (3.3×10^{34} ergs s^{-1}). Efficiencies approaching 100% are achieved by the least luminous γ-ray pulsars. Fortunately, several future observations have the potential to confirm this scenario in detail. A pulsar detection is possible in a long observation with *XMM-Newton* or with the *Chandra* High-Resolution Camera if RX J1836.2+5925 is an "ordinary" pulsar, with $P > 50$ ms and X-ray pulsed fraction $\geq 15\%$, as is common for thermally emitting neutron stars that are also EGRET sources. We have also not given up on obtaining a radio pulsar detection. Finally, the *Gamma-ray Large Area Space Telescope* (GLAST) may itself be able to detect pulsations from 3EG J1835+5918 if a sufficiently long observation is made.

We thank Andrew Lyne for obtaining the radio data at Jodrell Bank, and the referee Patrizia Caraveo for helpful suggestions. This work was supported by grants SAO GO2-3071X and HST GO-09278.01A. The ability to obtain coordinated *Chandra* and *HST* observations under a joint proposal opportunity enabled us to achieve these results in a timely and efficient manner.

REFERENCES

Bignami, G. F., & Caraveo, P. A 1996, ARA&A, 34, 331
Burke, B. E., Gregory, J., Bautz, M. W., Prigozhin, G. Y., Kissel, S. E., Kosicki, B. N., Loomis, A. H., & Young, D. J. 1997, IEEE Trans. Electron Devices, 44, 1633
Camilo, F., et al. 2002a, ApJ, 571, L41
Camilo, F., Manchester, R. N., Gaensler, B. M., Lorimer, D. R., & Sarkissian, J. 2002b, ApJ, 567, L71
Caraveo, P. A., Bignami, G. F., Mignani, R., & Taff, L. G. 1996, ApJ, 461, L91
Gehrels, N., et al. 2000, Nature, 404, 363
Grenier, I. A. 2000, A&A, 364, L93
Halpern, J. P., & Ruderman, M. 1993, ApJ, 415, 286
Halpern, J. P., & Wang, F. Y.-H. 1997, ApJ, 477, 905
Harding, A. K., & Zhang, B. 2001, ApJ, 548, L37
Hartman, R. C., et al. 1999, ApJS, 123, 79
Helfand, D. J. 1994, MNRAS, 267, 49
Kaaret, P., & Cottam, J. 1996, ApJ, 462, 35
McLaughlin, M. A., Cordes, J. M., Hankins, T. H., & Moffett, D. A. 1999, ApJ, 512, 929
Mirabal, N., Halpern, J. P., Eracleous, M., & Becker, R. H. 2000, ApJ, 541, 180 (Paper I)
Mirabal, N., & Halpern, J. P. 2001, ApJ, 547, L137 (Paper II)
Nice, D. J., & Sayer, R. W. 1997, ApJ, 476, 261
Ögelman, H., & Finley, J. P. 1993, ApJ, 413, L31
Reimer, O., Brazier, K. T. S., Carramiñana, A., Kanbach, G., Nolan, P. L., & Thompson, D. J. 2001, MNRAS, 324, 772
Rejkuba, M., Minniti, D., Gregg, M. D., Zijlstra, A. A., Alonso, M. V., & Goudfrooij, P. 2000, AJ, 120, 801
Taylor, J. H., & Cordes, J. M. 1993, ApJ, 411, 674
Thompson, D. J., Harding, A. K., Hermsen, W., & Ulmer, M. P. 1997, in AIP Conf. Proc. 410, Proc. Fourth Compton Symp., ed. C. D. Dermer, M. S. Strickman, & J. D. Kurfess (New York: AIP), 39
Thompson, D. J., et al. 1999, ApJ, 516, 305
Totani, T., Kawasaki, W., & Kawai, N. 2002, PASJ, in press
Wang, F. Y.-H., Ruderman, M., Halpern, J. P., & Zhu, T. 1998, ApJ, 498, 373
Yadigaroglu, I. A., & Romani, R. W. 1997, ApJ, 476, 347
Yakovlev, D. G., Gnedin, O. Y., Kaminker, A. D., & Potekhin, A. Y. 2002, in Proc. 270 Heraeus Seminar on Neutron Stars, Pulsars and Supernova Remnants, submitted (astro-ph/0204226)
Zavlin, V. E., Pavlov, G. G., Sanwal, D., Manchester, R. N., Trümper, J., Halpern, J. P., & Becker, W. 2002, ApJ, 569, 894