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DISCOVERY OF AN EXTRAGALACTIC MAGNETAR FLARE IN THE *BATSE* CATALOG

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ABSTRACT

The three magnetar flares that have been observed within our galaxy are characterized by short (~ 0.3 s), energetic ($\sim 10^{43}$–10^{46} ergs) gamma-ray spikes followed by less energetic ($\sim 10^{43}$–10^{44} ergs), softer ($kT \approx 25$ keV) pulsating ($T = 5-8$ s) tails. To identify extragalactic magnetar flares one can examine (a) their positions relative to nearby galaxies, (b) their spike spectra, and (c) their periodic tails. We have focused on the last of these by generating Lomb periodograms for the emission following short bursts detected by the *Burst and Transient Source Experiment* (*BATSE*). Out of 358 short bursts examined, one has a significant tail periodicity (T = 13.8 seconds, $P = 4 \times 10^{-5}$). The most probable host galaxy for this burst is the spiral galaxy NGC 6946 (d = 5.9 Mpc). At this distance, the energy of the spike, $(2.7 \pm 0.3) \times 10^{44}$ ergs, is akin to those of the galactic magnetar giant flares, as are its duration (~ 0.4 s) and temperature (250 ± 60 keV). For the tail emission, however, our estimated temperature of 60 ± 5 keV is harder and the energy release of $(4.3 \pm 0.8) \times 10^{45}$ ergs is larger than those of the galactic magnetar flares. The energy in the tail implies a magnetic field $B_\star > 1.4 \times 10^{15}$ G, the largest dipole field strength yet to be observed for a magnetar.

Subject headings: gamma rays: bursts–stars: neutron–X-rays: stars

1. INTRODUCTION

Three times within the past thirty years, intense gamma-ray flares have erupted from the sources of the much fainter soft-gamma repeaters (SGRs). The first was detected on 1979 March 5 from the direction of young supernova remnant, N49, in the Large Magellenic Cloud (Evans et al. 1980; Cline et al. 1982). Perhaps more striking than its brilliance, was its clearly fading tail with a periodicity of 8.1 seconds (Barat et al. 1979; Terrell et al. 1980). Repeated weaker outbursts with a soft spectral peak prompted the eventual acceptance of the previously unknown SGRs as a phenomena separate from the more common gamma-ray bursts (GRBs). While other SGR sources were discovered, the intense 1979 March 5 event remained unique among gamma-ray transients until 1998 August 27 when a similar event was detected with a tail periodicity of 5.16 seconds from SGR 1900+14 (Hurley et al. 1999b; Feroci et al. 1999, 2001). A third giant flare erupted from SGR 1806-20 on 2005 December 27 with an energy release nearly 100$\times$ greater than those of the previous two (Hurley et al. 2005; Palmer et al. 2005).

A model proposed by Duncan & Thompson (1992; Thompson & Duncan 2001) has had considerable success in explaining SGRs, their quiescent emission, and the occasional giant flares. In it, neutron stars with magnetic fields ($B \approx 10^{15}$ Gauss) much stronger than typical radio pulsars ($B \approx 10^{12}$ Gauss) occasionally emit soft gamma rays during crustal "starquakes." On rarer occasions, they release much more energy in the shearing and reconnection of their intense magnetic fields, which presumably is the cause of the giant flares observed. In this model, the source of the periodic tail emission is a thermal $e^{\pm}$ pair fireball trapped in the rotating star's magnetosphere.

As can be seen in Table 1, all three flares are characterized by a short (0.2-0.35 s), intense gamma-ray spike following by a softer ($kT \sim 25$ keV) tail with a periodic variability of a few seconds. Assuming that our galaxy is not unique, then magnetar flares also occur in nearby galaxies. Based on the peak fluxes of the first two magnetar flares, Duncan (2001) estimated that ~ 12 of these might have already been detected out to ~ 13 Mpc by the *Burst and Transient Source Experiment* (*BATSE*). At such distances, magnetar flares would be difficult to identify since the characteristic pulsating tail would be at or below the level of the background. Instead, they would likely be labeled as short GRB, since the spectrum of the initial spike is similar to that of classical "GRB" (Fenimore et al. 1996). To identify extragalactic magnetar flares amid short gamma-ray bursts, one can exploit three distinguishing attributes: (a) their locations relative to nearby galaxies, (b) their spectral temperatures, and (c) their faint oscillating tails.

Three recent searches for extragalactic magnetar flares focusing on the first two attributes have not identified any clear candidates. Using the *Third Interplanetary Network* (Hurley et al. 1999a) of gamma-ray detectors, Nakar et al. (2005) have recently found no nearby (< 500 Mpc) host galaxies for five well-localized (3σ error box ≤ 100 arcmin^2 GRB. Popov & Stern (2005) examined the proximity of short bursts to galaxies with high star formation rates that sit just beyond the Local Group and found no candidates with appropriate hardness ratios. Finally, Lazzati et al. (2005) searched for short GRB with blackbody spectra akin to the one reported for the 2005 December 27 flare, but found no such bursts had appropriate host galaxies. In this study, we will search for the faint, periodic tails in the emission that follows short GRB.

A search for periodic emission following short GRBs detected by *Pioneer Venus Orbiter* revealed that it was not sensitive enough to detect pulsations akin to those of the 1979 March 5 event (Crider & Fenimore 1996). This new search employs data from *BATSE*, the most sensitive GRB detector ever flown until the launch of *Swift* in 2004 (Band 2003). In time, the localization capabilities of the *Swift* gamma-ray burst mission (Gehrels et al. 2004) should allow clear identification of extragalactic magnetar flares and their host galaxies. However as of this writing, only two short bursts exist in the *Swift* catalog.

TABLE 1
PROPERTIES OF THE THREE GALACTIC MAGNETAR FLARES AND GRB 970110.

	1979 March 5	1998 August 27	2004 December 27	1997 January 10	References
Coincident SGR	SGR 0526-66	SGR 1900+14	SGR 1806-20	...	...
Host Candidate	N49	G42.8+0.6[a]	G10.0-0.3	NGC 6946	1, 2, 3
Host Distance (kpc)	50 ± 1	~ 7[b]	$15.1^{+1.8}_{-1.3}$[c]	5900 ± 400	4, 5, 6, 7
Spike Properties					
Duration (s)	~ 0.25	~ 0.35	~ 0.2	~ 0.4	8, 9
Energy (ergs)	1.3×10^{44}	3.2×10^{43}	$(3.7 \pm 0.9) \times 10^{46}$	$(2.7 \pm 0.3) \times 10^{44}$	8, 9
$kT_{\rm OTTB}$ (keV)	246	240	175 ± 25 ($kT_{\rm BB}$)	250 ± 60	9, 10, 11
Tail Properties					
Energy (ergs)	3.0×10^{44}	2.6×10^{43}	1.2×10^{44}	$(4.3 \pm 0.8) \times 10^{45}$	8, 9
Fraction of Total Energy	75%	44%	0.3%	94%	...
Minimum $B_{\rm dipole}$ (G)	4×10^{14}	1×10^{14}	2×10^{14}	1.4×10^{15}	...
$kT_{\rm OTTB}$ (keV)	~ 30	~ 20	~ 22	60 ± 5	8, 9
P (s)	8.1	5.16	7.56	13.8	8, 9
$\dot{P}$ (s s^{-1})	$6.6(5) \times 10^{-11}$	1.1×10^{-10}[e]	$(8.3 \pm 0.3) \times 10^{-11}$	$\gtrsim 1.4 \times 10^{-10}$	12, 13, 14

REFERENCES. — (1) Evans et al. 1980; Cline et al. 1982; (2) Vasisht et al. 1994; (3) Hurley et al. 1994; (4) Persson et al. 2004; (5) Hurley et al. 1999c (6) Corbel & Eikenberry 2004; Eikenberry et al. 2004; (7) Drozdovsky et al. 2001; (8) Mazets et al. 1999; (9) Hurley et al. 2005; (10) Fenimore et al. 1996; (11) Hurley et al. 1999b; (12) Kulkarni et al. 2003; (13) Kouveliotou et al. 1999; (14) Kouveliotou et al. 1998

NOTE. — All energies are based on the reported gamma-ray fluences (in ergs cm^{-2}) and are calculated for the candidate host distances listed above. The values for the minimum magnetic dipole $B_{\rm dipole}$ assume a magnetar radius $R_\star$ = 10 km and the outer radius of the magnetic field loop ΔR = 10 km, as described in Equation 2.

[a]This relationship has been questioned in (Lorimer & Xilouris 2000).
[b]While X-ray attenuation suggest 5 kpc, G42.8+0.6 may be as far as 10 kpc.
[c]Figer et al. (2004) found d = 11.8 kpc based on the near-infrared spectra of LBV 1806-20.
[d]Marsden et al. (1999) found 6×10^{-11} s s^{-1}.

2. PROCEDURES

The *BATSE* 4B Catalog (Paciesas et al. 1999) included 1637 bursts detected between 1991 April 19 and 1996 August 29. Additional bursts triggered *BATSE* up to 2000 May 26. The current *BATSE* catalog (http://www.batse.msfc.gov/) contains 2702 gamma-ray bursts triggered during it 9.1 years of burst detection. As the intense peaks of the three galactic magnetars were less than 1 second, we begin by selecting those *BATSE* bursts with T_{90} durations (the period encompassing 90% of the photon counts) less than 1 second. Of the 2041 bursts with calculated T_{90} durations, 358 had $T_{90} < 1.0$ s.

To identify magnetar tails, we constructed periodograms for the 100-second intervals that immediately followed each of our short GRBs. We began with 64-ms lightcurves concatenated from three *BATSE* data types (DISCLA, PREB, and DISCSC) and maintained by the Compton Science Support Center (http://cossc.gsfc.nasa.gov/). Since we were primarily interested in the period immediately following short bursts, most of our data would have originally been DISCSC, which covers the minutes just after the trigger. We discarded data in the upper three channels, as 75-95% of the signal should be in the lowest channel, based on the spectra reported for the galactic magnetar flares. While polynomial background fits already have been calculated by the *BATSE* team, we found that while these were valid for the burst duration, they were not necessarily correct for the 100-second interval following the burst. We refit polynomial backgrounds for each burst using data that spanned from 100 seconds before to 200 seconds after the trigger and excluded a 20-second window centered on the burst spike. We then generated a Lomb periodogram (Press et al. 1992) for each short GRB's post-burst emission. This powerful tool can extract a periodicity that is not readily apparent in the time history, as is illustrated by the example in Figure 13.8.1 of Press et al. (1992). An advantage of this algorithm over the more common Fast Fourier Transform is that it robustly estimates the probability of the null hypothesis that a given peak is a random fluctuation in the noise.

3. RESULTS

Of the 358 bursts analyzed, only one had a significance above our predetermined threshold of $P = 3 \times 10^{-3}$, based on the number of bursts analyzed. The periodogram plotted in Figure 1 for GRB 970110 (*BATSE* #5770) had peak periodicity of 13.8 seconds with a Lomb power of 17.8. The chance probability of a periodicity this powerful suggests this feature is highly significant ($P = 3 \times 10^{-5}$). Examining the 50-100 keV channel independently reveals the same strong periodicity of 13.8 seconds, with a Lomb power of 16.2 and a significance $P = 1 \times 10^{-4}$. No significant signal was found in the upper two channels during the 100-second period after the trigger, revealing that most of periodic emission was emitted below 100 keV. While no periodic tail is immediately obvious in the light curve of this emission (available at http://cossc.gsfc.nasa.gov/), we should not expect to see one. The spike peak fluxes of the three galactic magnetars were each $> 10\times$ greater than the early flux of the tail. Thus, we expect that periodic tail emission should be near the level of the background and only detectable with a periodogram. (Any more obvious periodic signal certainly would have already been discovered and reported as a magnetar candidate.) The Australia Telescope National Facility (ATNF) Pulsar Catalog (Manchester et al. 2005) that includes the known gamma-ray pulsars and the anomalous X-ray pulsars contains no sources with a periodicity > 2 s inside the 99.7% confidence location of GRB 970110. A periodogram of the pre-burst (-100-to-0 s) and subsequent (100-to-200 s) emission revealed no signifi-

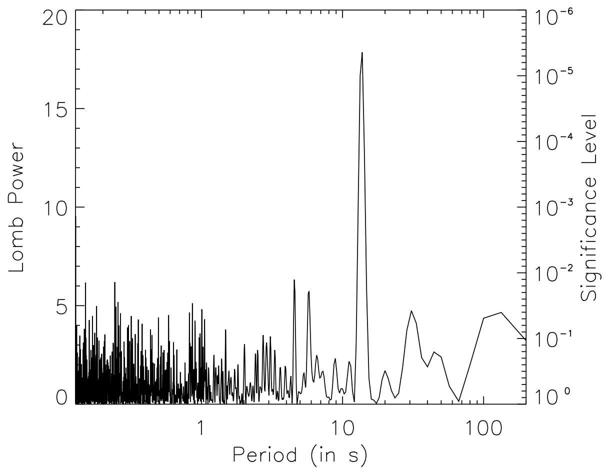

FIG. 1.— Lomb periodogram of the 100-s interval following GRB 970110 (*BATSE* #5770). The dominant periodicity of 13.8 seconds had a Lomb power of 17.8. The chance probability of such an intense peak ($P = 3\times10^{-5}$) is very low, suggesting that this is a real feature.

cant periodicity, with maximum significances of $P = 0.55$ and 0.45 respectively. While the 1.024-second binning of the pre-burst emission limits the sensitivity of the Lomb periodogram to some extent, the period of interest (0-to-100 s) retains a marginally significant spike ($P = 0.01$) when resampled to this resolution. This lack of a periodic signal immediately before or 100-seconds after the triggers implies that the pulsations are indeed a transient phenomena associated with the spike. The properties of GRB 970110 appear in Table 1 alongside those of the galactic magnetar flares.

The duration of the spike (~ 0.4 s) is very similar to those of the magnetar flares, though this might be expected given that we were only analyzing short GRBs. Using the *rmfit* analysis software developed at NASA-MSFC and DISCSC data from the *BATSE* Large Area Detectors, we found a similar spike spectrum, as well. An optically-thin thermal bremsstrahlung (OTTB) photon spectrum

$$F = A(\frac{E}{100\ \mathrm{keV}})^{-1}\exp(-\frac{E}{kT_{\mathrm{BB}}}) \qquad (1)$$

gives an acceptable fit ($\chi^2 = 1.32, \nu = 2, P = 0.52$) with a temperature $kT_{\mathrm{OTTB}} = 250\pm60$ keV. Fitting a blackbody spectrum instead gives a much poorer fit ($\chi^2 = 8.2, \nu = 2, P = 0.017$) with $kT_{\mathrm{BB}} = 30$ keV. Our result is consistent with the peak spectrum of the 1979 March 5 event ($kT_{\mathrm{OTTB}} = 246$ keV; Fenimore et al. 1996), but is softer than the blackbody spectrum of the 2004 December 27 flare ($kT_{\mathrm{BB}} = 175\pm25$ keV; Hurley et al. 2005). Using $rmfit$, we found the fluence of the spike to be $(6.5\pm0.5)\times10^{-8}$ erg cm^{-2} in *BATSE*'s 25-2000 keV window.

Determining the spectrum and fluence of the tail emission requires a calibration between the measured Lomb power and the total number of counts detected in each channel. To explore the sensitivity of our procedure, we simulated extragalactic magnetar flare tails using the *Swift* BAT light curve for the 2004 December 27. Since this flare passed through the backside of *Swift*, we can only use this data to provide a time profile for our simulated events. Furthermore, we can only use data that occurred between 205 and 505 seconds after the trigger, as *Swift* slewed twice during the first 200 seconds of the flare, causing the flux to artificially rise and fall.

We then created several synthetic magnetar flares for each *BATSE* channel, with total counts ranging from 200 to 400,000. Calculating a periodogram for each allowed us to estimate the functional relationship between the integrated detected counts in a channel and the Lomb power, which is roughly quadratic in the region of interest. We found our Lomb powers of 17.7 in channel 0 and 16.2 in channel 1 corresponded to 6000 counts and 5100 counts, respectively. We next convolved OTTB spectrum with kT_{OTTB} ranging from 5 to 30 keV with the detector response matrix for *BATSE* trigger #5770 to determine the number of counts expected in the four DISCSC channels. From this, we estimated that the temperature of the tail is $kT_{\mathrm{OTTB}} = 60\pm5$ keV, notably harder than other magnetar flares. With this spectrum, and the Lomb power for channel 0, we estimate a tail energy fluence of $(7.5\pm1.5)\times10^{-7}$ erg cm^{-2}. The fraction of the total energy in the tail emission (94%) is much larger than the recent 2004 December 27 event (0.3%), but is comparable to the 1979 March 5 event (75%).

3.1. *Candidate Host Galaxies*

The *BATSE* localization of GRB 970110 in Figure 2 reveals only a handful of potential host galaxies that are nearby. As magnetars have relatively short lifetimes, we expect to find them in areas of high star formation. For this paper, we will assume that the star formation rate of a galaxy is proportional to its blue luminosity L. The galactic magnetar flare rate is 1.0 ± 0.6 decade$^{-1}L_{\mathrm{MWG}}{}^{-1}$, where $L_{\mathrm{MWG}}{}^{-1}$ is the blue luminosity of the Milky Way galaxy (6.4×10^{43} erg s^{-1}; Karachentsev et al. 2004). While the dwarf spheroidal galaxy Draco (d = 0.08 Mpc) and the blue compact dwarf galaxy NGC 6789 (d = 3.6 Mpc) both fall just inside of the 95.4% confidence circle, these both have very low *a priori* probabilities of producing a magnetar flare based on their star formation rates. Instead, we find a Bayesian probability of 87% that of the candidates examined, NGC 6946, the "Fireworks Galaxy" (d = 5.9 Mpc), is the host. While it is just outside of the 95.4% confidence circle, its very high star formation rate (3.12 $M_\odot$ yr^{-1}; Karachentsev et al. 2005) makes it the most likely source. Based on its blue luminosity and *BATSE*'s 4.6-year exposure (9.1 year lifetime, 50% coverage), we find there is a 38% *a priori* probability that a magnetar flare from NGC 6946 exists in the *BATSE* catalog.

Assuming NGC 6984's distance of 3.6 Mpc and isotropic emission, the energy fluence in the spike corresponds to $(2.7\pm0.3)\times10^{44}$ erg, very comparable to 1979 March 5 flare from SGR 0526-66, which had a spike energy of 1.2×10^{44} erg (Mazets et al. 1979). This distance also implies a tail energy of $(4.3\pm0.8)\times10^{45}$ ergs, larger than those of the three galactic magnetar flares, but only $\sim 10\times$ more than that of the 1979 March 5 event.

4. DISCUSSION

The duration of GRB 970110, its initial spectrum, its proximity to a nearby galaxy with active star formation, and its energetics are all consistent with the hypothesis that it is in fact an extragalactic magnetar flare. It is the highly significant periodic tail, however, that makes this hypothesis probable rather than merely possible. Our discovery of such an energetic magnetar tail extends the range to which we expect to measure magnetar periods. Hurley et al. (2005) calculated that magnetar periods might be measured by *Swift* out to a distance of $\sim 2-8.5$ Mpc based on the fluence observed for

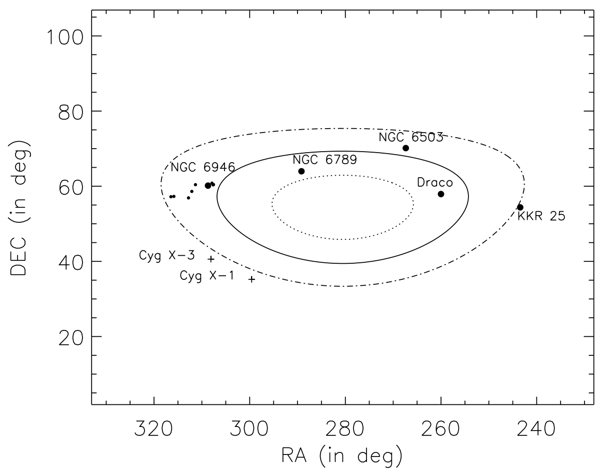

FIG. 2.— The localization of GRB 970110 (*BATSE*#5770) and galaxies closer than 10 Mpc (taken from the catalog of Karachentsev et al. 2004). The localization of GRB 970110 has a center at $18^{\mathrm{h}}42^{\mathrm{m}}12^{\mathrm{s}}$, $54°23'$ and an statistical error radius of $\sigma_{\mathrm{stat}} = 8.00°$. Including the "core-plus-tail" systematic error distribution (Model 2) of Briggs et al. (1999), we find 68.3%, 95.4%, and 99.7% confidence circles of 8.5°, 14.9°, and 21.0°. While the blue compact dwarf galaxy NGC 6789 (d = 3.6 Mpc) and the dwarf spheroidal galaxy Draco (d = 0.08 Mpc) both fall inside the 95.4% confidence circle, the very high star formation rate of NGC 6946 and it proximity to GRB 970110 ($\Delta\theta$ = 16.1°) make it the most probable host galaxy. The labels of the companion dwarf galaxies of NGC 6946 have been omitted for clarity.

the 2004 December 27 event. Approximately 15% of the tail energy in the 1997 January 10 event (6.5×10^{44} ergs) was released in the *Swift* XRT band (0.3-100 keV), suggesting that this detection range can be extended to $\sim 5-20$ Mpc. The tail energy also places limits on the magnetic field strength. For a magnetar to confine the fireball that produces the tail emission,

$$B_\star > 1.4 \times 10^{15} \left(\frac{E_{\mathrm{tail}}}{4.3 \times 10^{45}\ \mathrm{erg}}\right)^{1/2} \left(\frac{\Delta R}{10\ \mathrm{km}}\right)^{-3/2} \left(\frac{1+\Delta R/R_\star}{2}\right)^{3} \mathrm{G} \qquad (2)$$

where $B_\star$ is the dipole magnetic field strength of the magnetar, $R_\star$ is the stellar radius, and ΔR is the outer radius of the magnetic loop confining the plasma (Thompson & Duncan 1995). As this was the largest tail energy yet observed, this places the highest lower limit on the dipole magnetic field strength for a magnetar (see Table 1). We can use the field strength to place limits on the spindown rate also. If we make the simplistic assumption that the magnetar loses rotational energy primarily to magnetic dipole radiation (Michel 1991), we find

$$\dot{P} = 1.4 \times 10^{-10} \left(\frac{B_\star}{1.4 \times 10^{15}\ \mathrm{G}}\right)^{2} \left(\frac{P}{13.8\ \mathrm{s}}\right)^{-1} \mathrm{s\ s^{-1}} \qquad (3)$$

which is similar to those of the galactic magnetars, particularly SGR 1900+14.

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REFERENCES

Band, D. L. 2003, ApJ, 588, 945
Barat, C., Chambon, G., Hurley, K., Niel, M., Vedrenne, G., Estulin, I. V., Kurt, V. G., & Zenchenko, V. M. 1979, A&A, 79, L24+
Briggs, M. S., Pendleton, G. N., Kippen, R. M., Brainerd, J. J., Hurley, K., Connaughton, V., & Meegan, C. A. 1999, ApJS, 122, 503
Cline et al. 1982, ApJ, 255, L45
Corbel, S., & Eikenberry, S. S. 2004, A&A, 419, 191
Crider, A., & Fenimore, E. E. 1996, in American Institute of Physics Conference Series, 926–929
Drozdovsky, I. O., Schulte-Ladbeck, R. E., Hopp, U., Crone, M. M., & Greggio, L. 2001, ApJ, 551, L135
Duncan, R. C. 2001, in AIP Conf. Proc. 586: 20th Texas Symposium on relativistic astrophysics, 495–+
Duncan, R. C., & Thompson, C. 1992, ApJ, 392, L9
Eikenberry et al. 2004, ApJ, 616, 506
Evans et al. 1980, ApJ, 237, L7
Fenimore, E. E., Klebesadel, R. W., & Laros, J. G. 1996, ApJ, 460, 964
Feroci, M., Frontera, F., Costa, E., Amati, L., Tavani, M., Rapisarda, M., & Orlandini, M. 1999, ApJ, 515, L9
Feroci, M., Hurley, K., Duncan, R. C., & Thompson, C. 2001, ApJ, 549, 1021
Figer, D. F., Najarro, F., & Kudritzki, R. P. 2004, ApJ, 610, L109
Gehrels et al. 2004, ApJ, 611, 1005
Hurley et al. 2005, Nature, 434, 1098
Hurley, K., Briggs, M. S., Kippen, R. M., Kouveliotou, C., Meegan, C., Fishman, G., Cline, T., & Boer, M. 1999a, ApJS, 122, 497
Hurley et al. 1999b, Nature, 397, 41
Hurley, K., Kouveliotou, C., Woods, P., Cline, T., Butterworth, P., Mazets, E., Golenetskii, S., & Frederics, D. 1999c, ApJ, 510, L107
Hurley, K., Sommer, M., Kouveliotou, C., Fishman, G., Meegan, C., Cline, T., Boer, M., & Niel, M. 1994, ApJ, 431, L31
Karachentsev, I. D., Kajsin, S. S., Tsvetanov, Z., & Ford, H. 2005, A&A, 434, 935
Karachentsev, I. D., Karachentseva, V. E., Huchtmeier, W. K., & Makarov, D. I. 2004, AJ, 127, 2031
Kouveliotou, C., Dieters, S., Strohmayer, T., van Paradijs, J., Fishman, G. J., Meegan, C. A., Hurley, K., Kommers, J., Smith, I., Frail, D., & Murakami, T. 1998, Nature, 393, 235
Kouveliotou et al. 1999, ApJ, 510, L115
Kulkarni, S. R., Kaplan, D. L., Marshall, H. L., Frail, D. A., Murakami, T., & Yonetoku, D. 2003, ApJ, 585, 948
Lazzati, D., Ghirlanda, G., & Ghisellini, G. 2005, MNRAS, L58+
Lorimer, D. R., & Xilouris, K. M. 2000, ApJ, 545, 385
Manchester, R. N., Hobbs, G. B., Teoh, A., & Hobbs, M. 2005, AJ, 129, 1993
Marsden, D., Rothschild, R. E., & Lingenfelter, R. E. 1999, ApJ, 520, L107
Mazets, E. P., Cline, T. L., Aptekar', R. L., Butterworth, P. S., Frederiks, D. D., Golenetskii, S. V., Il'Inskii, V. N., & Pal'Shin, V. D. 1999, Astronomy Letters, 25, 635
Mazets, E. P., Golentskii, S. V., Ilinskii, V. N., Aptekar, R. L., & Guryan, I. A. 1979, Nature, 282, 587
Michel, F. C. 1991, Theory of neutron star magnetospheres (Chicago, IL, University of Chicago Press, 1991, 533 p.)
Nakar, E., Gal-Yam, A., Piran, T., & Fox, D. B. 2005, ArXiv Astrophysics e-prints
Paciesas et al. 1999, ApJS, 122, 465
Palmer et al. 2005, Nature, 434, 1107
Persson, S. E., Madore, B. F., Krzemiński, W., Freedman, W. L., Roth, M., & Murphy, D. C. 2004, AJ, 128, 2239
Popov, S. B., & Stern, B. E. 2005, ArXiv Astrophysics e-prints
Press, W. H., Flannery, B. P., Teukolsky, S. A., & Vetterling, W. T. 1992, Numerical Recipes: The Art of Scientific Computing, 2nd edn. (Cambridge (UK) and New York: Cambridge University Press)
Terrell, J., Evans, W. D., Klebesadel, R. W., & Laros, J. G. 1980, Nature, 285, 383
Thompson, C., & Duncan, R. C. 1995, MNRAS, 275, 255
—. 2001, ApJ, 561, 980
Vasisht, G., Kulkarni, S. R., Frail, D. A., & Greiner, J. 1994, ApJ, 431, L35