THE ASTROPHYSICAL JOURNAL, 486:1013–1018, 1997 September 10
© 1997. The American Astronomical Society. All rights reserved. Printed in U.S.A.

ROSAT POSITION OF GRO J1744−28 AND SEARCH FOR ITS NEAR-INFRARED COUNTERPART

T. AUGUSTEIJN,[1] J. GREINER,[2] C. KOUVELIOTOU,[3] J. VAN PARADIJS,[4,5] C. LIDMAN,[1] P. BLANCO,[6]
G. J. FISHMAN,[7] M. S. BRIGGS,[5] J. KOMMERS,[8] R. RUTLEDGE,[8] W. H. G. LEWIN,[8]
A. A. HENDEN,[3,9] C. B. LUGINBUHL,[9] F. J. VRBA,[9] AND K. HURLEY[10]
Received 1996 November 1; accepted 1997 March 13

ABSTRACT

We report the detection with *ROSAT* of a transient X-ray source at R.A. $17^h44^m33^s.1$ and decl. $-28°44'29''$ (J2000), which we identify with the transient bursting pulsar GRO J1744−28. We have made *K*-band observations of the X-ray source at ESO and the US Naval Observatory, Flagstaff Station. A *K*-band counterpart of this transient previously identified by us on an image taken 1996 February 8 by Blanco et al. is found to be detected during only two (of seven) short exposures of which this image is composed. We cannot definitely reject the reality of this variable object but feel that it is not possible to rule out an instrumental effect. The lack of a persistent *K*-band counterpart of GRO J1744−28 is consistent with the idea that the low-energy emission from this object is dominated by reprocessing of X-rays in an accretion disk.

Subject headings: pulsars: individual (GRO J1744−28) — stars: neutron — X-rays: stars

1. INTRODUCTION

Early in 1995 December a source of hard X-ray bursts near the Galactic center was discovered with BATSE (Fishman et al. 1995; Kouveliotou et al. 1996a). Initially, the burst intervals were as short as 3 minutes, but after a day the observed burst rate settled at ∼20 per day, at which rate the source kept emitting bursts until April 26; then the burst rate rapidly decreased. Bursts were no longer detected with BATSE after 1996 May 2. On 1995 December 12, a transient source of persistent hard X-ray emission, GRO J1744−28, was discovered near the burst source (Paciesas et al. 1996). This source is a 467 ms X-ray pulsar (Finger et al. 1996a) in an 11.8 day binary orbit and has a remarkably small mass function [$f(M) = 1.3 \times 10^{-4}\ M_\odot$; Finger, Wilson, & van Paradijs 1996b; Finger et al. 1996c]. The burst source and the pulsar are one and the same source (Kouveliotou et al. 1996b). Subsequent *Rossi X-Ray Timing Explorer* (*RXTE*) observations (Swank et al. 1996) showed that the 2–100 keV spectrum (both in the bursts and in persistent emission) of GRO J1744−28 is typical for X-ray pulsars. The average persistent BATSE (20–60 keV) flux of the source increased from $\lesssim 10^{-9}$ ergs cm^{-2} s^{-1} early in 1995 December to $\sim 4 \times 10^{-8}$ ergs cm^{-2} s^{-1} early in 1996 February; after that, the source intensity decayed monotonically to less than 10^{-9} ergs cm^{-2} s^{-1} by early 1996 May. GRO J1744−28 is very likely a low-mass X-ray binary (LMXB); several studies have been made of its evolutionary history on the basis of the assumption that this is the case (Daumerie et al. 1996; Lamb, Miller, & Taam 1996; Sturner & Dermer 1996; van Paradijs et al. 1997).

As is the case for the type II bursts from the Rapid Burster (Lewin et al. 1976), the bursts are most likely caused by an instability in the accretion flow to the neutron star, but the nature of the instability has not been established with certainty (Kouveliotou et al. 1996a; Lewin et al. 1996; Cannizzo 1996).

The initial BATSE error box of GRO J1744−28 (Fishman et al. 1995; Paciesas et al. 1996) was soon refined by time-delay measurements between the *Compton Gamma Ray Observatory* (*GRO*) and *Ulysses* (Hurley et al. 1995, 1996) and scanning observations with the *RXTE* (Swank et al. 1996). Subsequent error boxes determined with *MIR-Kvant*/TTM (1′; Borozdin et al. 1996) and *Granat*/SIGMA (3′; Bouchet et al. 1996) are consistent with the ∼1′ *RXTE* error box. The *RXTE* error box contains a rapidly variable radio source (Frail et al. 1996a, 1996b). Optical and near-infrared observations initially concentrated on this radio source (Cole et al. 1996; Blanco, Lidman, & Glazebrook 1996; Vanden Berk et al. 1996; Żytkow & Irwin 1996; Augusteijn et al. 1996a). The *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) ∼1′ error box (Dotani et al. 1996b) overlaps the *RXTE* error box but excludes the VLA source.

We report here on a *ROSAT* observation of GRO J1744−28 that provided a position of sufficient accuracy (∼10″) to allow meaningful searches for a stellar counterpart (see also Kouveliotou et al. 1996c; Augusteijn et al. 1996b, 1996c). This position is just outside the *RXTE* error box (Swank et al. 1996) but is consistent with the *ASCA* error box (Dotani et al. 1996b); the VLA source is located about 1.″5 from the *ROSAT* source. We obtained *K*-band images at ESO and the US Naval Observatory (USNO),

[1] European Southern Observatory, Casilla 19001, Santiago 19, Chile.
[2] Max-Planck-Institut für extraterrestrische Physik, 85740 Garching, Germany.
[3] Universities Space Research Association, 10227 Wincopin Circle, Columbia, MD 21044.
[4] Astronomical Institute Anton Pannekoek, Kruislaan 403, 1098 SJ Amsterdam; and Center for High-Energy Astrophysics, University of Amsterdam, 1009 DB Amsterdam, Netherlands.
[5] Department of Physics, Optics Building, University of Alabama, Huntsville, AL 35899.
[6] Center for Astrophysics and Space Sciences, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093.
[7] Space Science Laboratory, NASA Marshall Space Flight Center, Huntsville, AL 35805.
[8] Center for Space Research, Massachusetts Institute of Technology, 70 Vassar Street, Cambridge, MA 02139.
[9] US Naval Observatory, Flagstaff Station, Flagstaff, AZ 86002.
[10] Space Sciences Laboratory, University of California, Berkeley, Berkeley, CA 94720.

Flagstaff Station, in which we find a possible counterpart of GRO J1744−28; however, we cannot exclude the possibility that this object is an instrumental artifact.

2. *ROSAT* OBSERVATIONS

The XTE source position was observed with the *ROSAT* HRI on 1996 March 14 between UT 17:56 and UT 18:11, for a total of 820 s. The data were analyzed with the dedicated EXSAS software package (Zimmermann et al. 1994). Applying a maximum likelihood detection algorithm with a likelihood threshold greater than 8 results in the detection of one point source (at only 1′ off-axis angle) in the total field of view. This source is located at R.A. $17^h44^m33^s.1$ and decl. $-28°44'29''$ (J2000), with an estimated accuracy of 10″ (radius). This estimate of the positional accuracy includes a 5″ statistical error and the systematic boresight of 8″ (quadratically summed).

During the *ROSAT* observation, a total of 273 X-ray photons were detected. The BATSE records show that no bursts occurred during this period, which is consistent with the nonvariable light curve of the X-ray source. The average count rate of 0.33 counts s^{-1} corresponds to about 1 mcrab in the 0.1–2.4 keV photon energy range. For a power-law spectral model with a photon index given by $\alpha = -1.22$ and an absorbing column of $N_H = 5.1 \times 10^{22}$ cm^{-2} (Dotani et al. 1996a), the unabsorbed X-ray luminosity is $3 \times 10^{37} d_{10}^2$ ergs s^{-1} in the 0.1–2.4 keV range (d_{10} is the distance in units of 10 kpc).

We have searched for X-ray pulsations (period range = 450–500 ms) using the phase dispersion method (Stellingwerf 1978). None were detected, with an upper limit to the pulsation amplitude (half peak-to-peak for a sinusoidal pulse) of 50%. This result is consistent with the pulsation amplitudes measured with BATSE and *RXTE*, which decrease substantially toward lower photon energies (Kommers et al. 1996).

The *ROSAT* source is a transient. The source position was covered by several earlier *ROSAT* pointed observations of the Galactic center region with both the PSPC and HRI and during the All-Sky Survey. The deepest available *ROSAT* pointing is a PSPC observation performed 1992 March 2–9, with an effective exposure time (including correction for off-axis effective area) of 34 ks. The (3 σ) upper limits to the count rate and X-ray flux (with the above-mentioned spectral model) are 2×10^{-4} counts s^{-1} and $4 \times 10^{33} d_{10}^2$ ergs s^{-1}, respectively, i.e., a factor of 1650 below the intensity observed in 1996 March.

In *ROSAT* observations of the galactic plane with exposure times of ∼800 s, one typically finds 1.5 X-ray sources deg^{-2}. Most of these (80%) are foreground (relatively unreddened) stars. We will make the conservative estimate that less than 50% of such stars show transient outbursts with amplitudes of a factor of 10^3. We then find that the probability of finding a transient source within 1.′5 of the XTE position of GRO J1744−28 is less than 10^{-4}. We conclude that it is highly unlikely that the *ROSAT* source is not GRO J1744−28.

3. SEARCH FOR A NEAR-INFRARED COUNTERPART

On 1996 March 28, between 09:31 and 09:46 UT, we obtained a deep K'-band image of a region containing the *ROSAT* error box, using the 2.2 m telescope at ESO. We used the IRAC-2B camera, with a 256 × 256 pixel NICMOS-3 HgCdTe array using lens *C*, which provides a 129″ × 129″ field, with a pixel size of 0.″507. To determine accurately the sky brightness across the field, the observation consisted of 12 mutually shifted individual images. The individual background-subtracted images were shifted onto a common coordinate frame and co-added.

The resulting image of the region near the *ROSAT* error box is shown in Figure 1*b*. In Figure 1*a* we show the same region as it appeared on another K'-band image taken by Blanco et al. (1996) on 1996 February 8 (exposure time = 600 s), using the same telescope and instrument setup. A comparison of the two images revealed a possible counterpart of GRO J1744−28: it is the object located 9.″5 due north of the best *ROSAT* position. This object, at R.A. $17^h44^m33^s.1 \pm 0^s.1$ and decl. $-28°44'19''.5 \pm 1''.5$ (epoch J2000), is present in the February 8 image but is absent on March 28 (Augusteijn et al. 1996b). Within the area that is covered by both images as shown in Figures 1*a* and 1*b*, we find no other objects that differ by more than 0.5 mag (at the 3 σ level).

Additional *K*-band imaging of the error box of GRO J1744−28 was obtained with a NICMOS-3 HgCdTe array detector at the USNO 1.55 m telescope in Flagstaff, giving an approximate 2.′3 × 2.′3 field of view with a 0.″54 pixel^{-1}

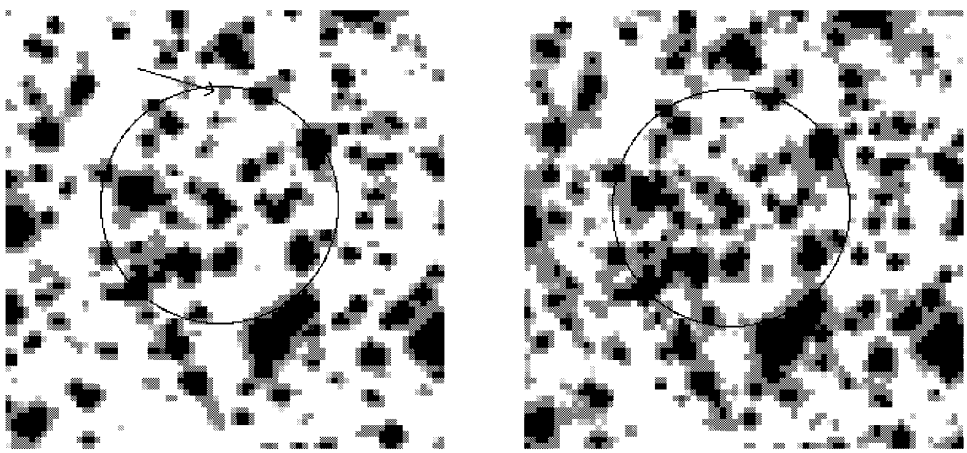

FIG. 1.—(*a*) Detail of a *K*-band image showing the 10″ (radius) *ROSAT* error box of GRO J1744−28. This image was taken on 1996 February 8. (*b*) Same as (*a*), but image taken on 1996 March 28. The variable object is indicated.

TABLE 1

INFRARED OBSERVATIONS

UT Date (1996)	Observatory	Number of Frames	Total Integration Time (s)	Seeing FWHM (arcsec)	Completeness Limit (K)	K(exp) (at 10 kpc)
Feb 8.....	ESO	10	600	1.0	16.3	16.0
Mar 2.....	USNO	9	270	4.4	13.6	16.5
Mar 3.....	USNO	9	270	3.5	13.9	16.6
Mar 7.....	USNO	9	270	4.6	13.6	16.6
Mar 8.....	USNO	9	270	3.8	14.5	16.5
Mar 28.....	ESO	12	600	1.1	16.0	16.9
Apr 1.....	USNO	4	120	3.2	14.7	16.9
Apr 2.....	USNO	15	450	4.2	13.6	16.9

scale. Six nights of observations were obtained (see Table 1). The four observations in early March were centered on the VLA source, while the two in early April were centered between the VLA and *ROSAT* positions. Fortunately, most of the early March pointings and all of the later pointings covered the *ROSAT* source. On each night, numerous slightly dithered frames of 30 s exposure time were obtained over a range of transparency conditions and relatively poor and variable seeing due to the large zenith distance from Flagstaff. These frames were flat-fielded and sky subtracted, and the best of these were coregistered to form a master frame for each night, producing a total on-target integration time of 120–450 s. There were approximately 800 K-band sources detected in these frames for which DAOPHOT profile-fitting photometry was obtained. On the basis of their normalized instrumental magnitudes, none of these sources were found to be variable. The K-band object seen in the ESO image was not detected in any of the USNO images.

Using the K magnitudes provided for three stars in the field by Blanco et al. (1996), we estimated the completeness limit to vary between 13.6 and 16.6, being highly dependent on the transparency and seeing conditions (the magnitude at which the photometric accuracy for a detected star of 0.3 mag is ~ 1.2 mag deeper).

A detailed analysis of the 10 subimages of which the February 8 ESO image is composed shows that the object is outside the frame of the detector in three of these and is present in only two of the remaining seven images (Augusteijn et al. 1996c; see Fig. 5 in Cole et al. 1997). We estimate that the K magnitude of this object during the two detections is ~ 14.5; the five nondetections correspond to $K > 16.5$.

At the time this frame was taken, no bursts were detected with the gamma-ray burst detector aboard the *Ulysses* spacecraft. Since the data during this time were clean and complete, and since the *Ulysses* spacecraft is not subject to Earth occultation, we conclude that no intense burst was emitted at this time. Unfortunately, GRO J1744−28, as seen from BATSE, was occulted by the Earth throughout the exposure.

The greater than 2 mag infrared brightness variations on a timescale of minutes without correlated X-ray variability raise the possibility that the images are an instrumental effect. The variable object produces signals in several pixels and has a point-spread function that is consistent with that of constant stars in the frame. However, because of the relatively large pixel size, the stellar images are undersampled and the profile for individual objects is poorly defined. The difference between the profile of a true star and, e.g., a cosmic event (which can affect more than one pixel) is, therefore, not very distinct. Furthermore, in both cases in which the object was detected, the center of the source as defined from point-spread function fitting was within 1 pixel of the upper edge of the array, and in neither case can the profile for the source be fully defined. We have carefully checked for any other starlike objects that do not appear in all images by blinking the individual images. Apart from obvious variations due to bad pixels, we found two cases in which an object appeared in only one image while the position was in the field of view of, in one case, seven and, in the other case, 10 images (see Figs. 2 and 3). In both cases the objects appeared at the edge of the image, covered several pixels, and had profiles indistinguishable from that of a star. In one case we also found an ellipse-shaped object covering several pixels that was seen in three consecutive images while it was in the field of view of all images (see Fig. 4). In one of these three images, the center of the object had moved by ~ 1–2 pixels, though still overlapping the area that was covered by the object in the other two images. The integrated brightness of this object is similar to that of the proposed counterpart.

The fact that the source is consistent with being a stellar point-spread function and was detected at different positions on the array but at the same position on the sky makes it hard to reject the reality of the variable object out of hand. However, given the reasons outlined above, we feel it is impossible to rule out the possibility that the two detections are caused by some instrumental effect. Note that on the basis of an analysis of the same 1996 February 8 frame, Cole et al. (1997) arrive at a different conclusion.

4. DISCUSSION

Our *ROSAT* observation has led to the detection of a transient X-ray source in the *ASCA* error box of GRO J1744−28, with a 10″ positional accuracy; the probability that it is not GRO J1744−28 is very small.

We have obtained K-band images during eight nights over the period 1996 February 8–April 2. Our February 8 image reveals a possible infrared counterpart near the edge of the *ROSAT* error box. However, the results presented in § 3 show that if this object is not an instrumental artifact, its properties are very unusual. Its K-band flux then changed by a factor of ~ 10 on a timescale of minutes, while no sudden X-ray enhancement was detected. This is hard to understand since reprocessing of X-rays in an accretion disk dominates the low-energy emission of LMXBs. According to the results of van Paradijs & McClintock (1994), an X-ray flux increase of a factor of $\sim 10^2$ should have accompanied the brief K-band flux increases, which is in disagree-

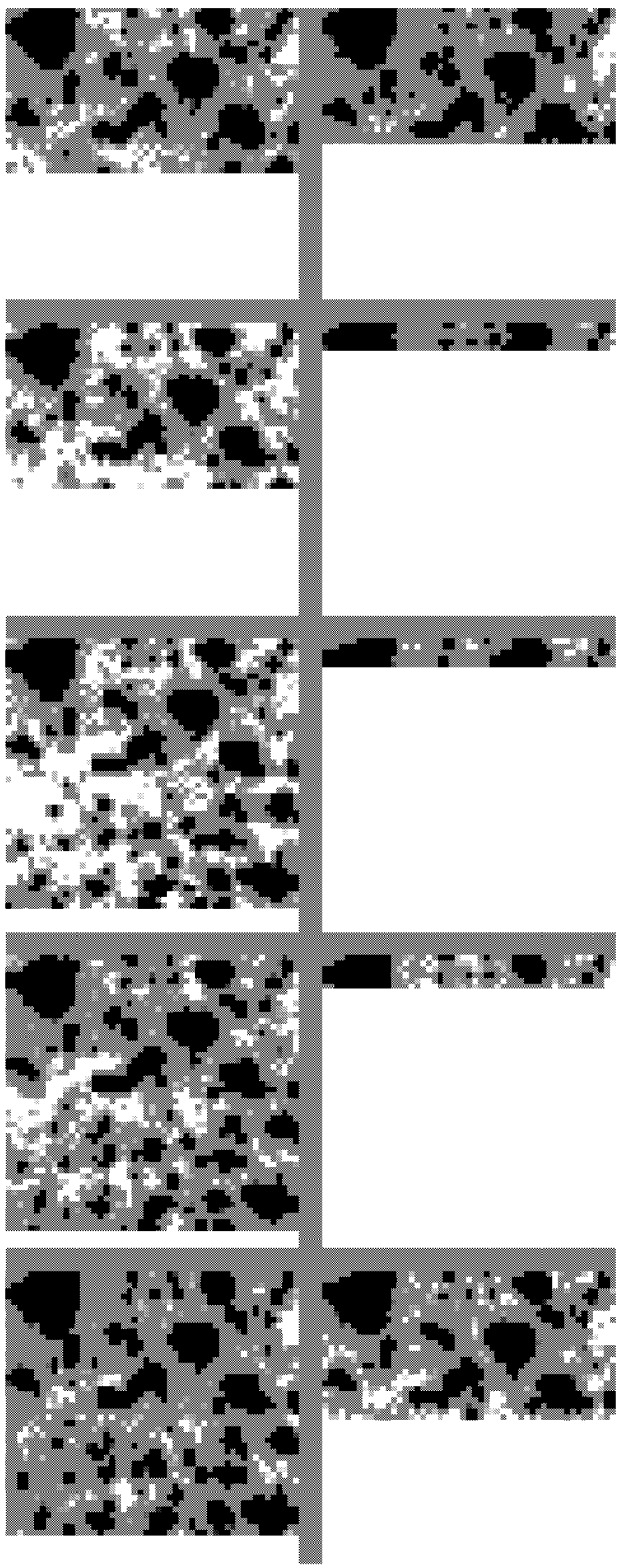

FIG. 2.—Collection of (parts of) the 10 exposures of which the 1996 February 8 image is composed, ordered chronologically downward from the top left and continuing from the top right. An object appears near the edge of the 10th frame but not in the other frames. The 10 frames are centered on this variable object at R.A. $17^h44^m37^s.8$ and decl. $-28°45'11''.7$.

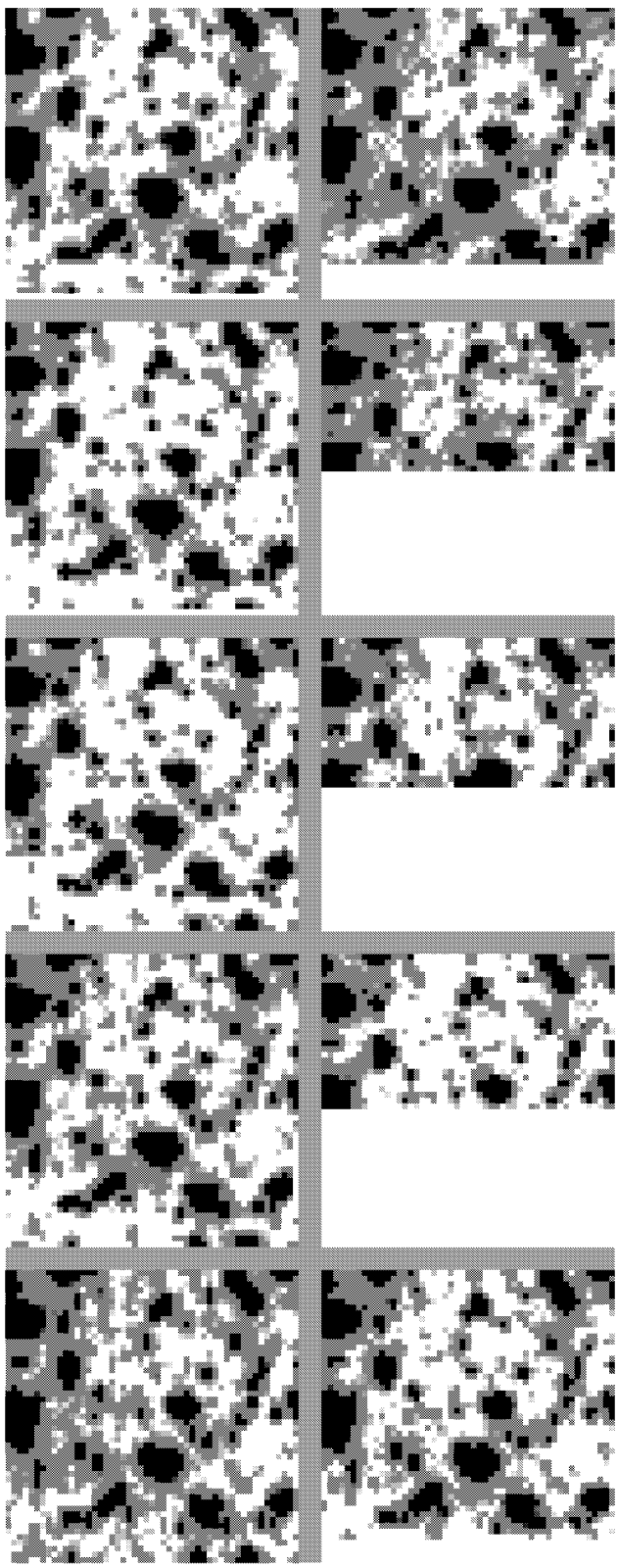

FIG. 3.—As in Fig. 2, but centered on R.A. $17^h44^m38^s.7$ and decl. $-28°45'08''.7$. An object appears near the edge of the eighth frame but not in the other frames.

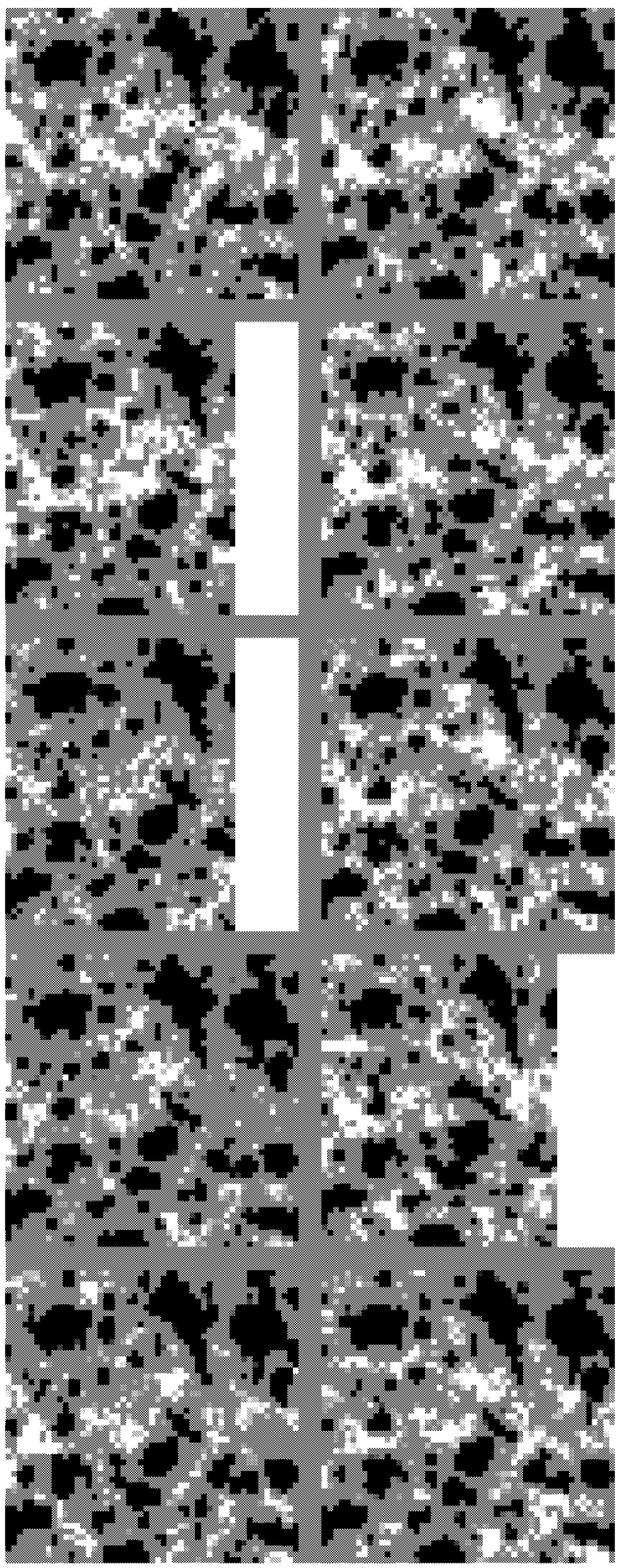

FIG. 4.—As in Fig. 2, but centered on R.A. $17^h44^m34\overset{s}{.}3$ and decl. $-28°46'11\overset{''}{.}0$. Near the center of the seventh, eighth, and ninth frames, an ellipse-shaped object is seen that is not detected in the other frames.

ment with the *Ulysses* data. One would require a nonthermal mechanism to produce the brief *K*-band flares. Nonthermal processes have also been invoked to explain radio bursts (Calla et al. 1979; Calla, Barathy, & Snagal 1980a, 1980b) and infrared bursts (Kulkarni et al. 1979; Jones et al. 1980) reported from the Rapid Burster (see Lewin et al. 1996 for a comparison of this source and GRO J1744−28). Lawrence et al. (1983) discussed extensive X-ray, radio, and infrared observations of the Rapid Burster made in 1979 and 1980, during which neither radio nor infrared bursts were detected; they concluded that it is unlikely that the radio bursts reported for the Rapid Burster were real, and that the reported infrared bursts were difficult to reconcile with the many null results during the 1979 and 1980 campaigns.

The nondetection of persistent *K*-band emission from GRO J1744−28 is consistent with what one expects for X-ray reprocessing in LMXBs. We will illustrate this in detail for the February 8 results. With the relation between $N_{\rm H}$ and interstellar extinction A_V (Predehl & Schmitt 1995) and a ratio $A_K/A_V = 0.112$ (Rieke & Lebofsky 1985), the observed column density of 5.1×10^{22} cm^{-2} corresponds to a *K*-band extinction of 3.1 mag. Since the accretion disk in GRO J1744−28 is likely to be quite hot (i.e., $T > 10^4$ K over most of the disk surface; see van Paradijs & McClintock 1995), we will take for its color index $(V-K)_0$, a value corresponding to those of hot stars: $(V-K)_0 = -0.9$ (Johnson 1966).

The absolute visual magnitudes of LMXBs with known distances and orbital periods are well represented by the relation $M_V = 1.57\ (\pm 0.24) - 2.27\ (\pm 0.32) \log \Sigma$, where $\Sigma = \gamma^{1/2}(P_{\rm orb}/1\ {\rm hr})^{2/3}$ and γ is the observed X-ray luminosity in units of the Eddington limit for a 1.4 $M_\odot$ neutron star (van Paradijs & McClintock 1994). On February 9, the persistent 2–60 keV flux measured with *RXTE* was 9.5×10^{-8} ergs cm^{-2} s^{-1}, which corresponds to $\gamma = 5.6 d_{10}^2$. With the orbital period of 11.8 days (Finger et al. 1996b, 1996c) the expected absolute visual magnitude, M_V(exp), then becomes $M_V({\rm exp}) = -3.0 - 2.27 \log d_{10}$; we then find the following for the expected *K* magnitude on 1996 February 8: $K({\rm exp}) = 16.0 + 2.73 \log d_{10}$.

Similarly, we have estimated *K*(exp) for all days of our observations (see Table 1) using the BATSE hard X-ray light curve of GRO J1744−28 (C. Wilson 1996, private communication), assuming that its X-ray spectrum did not change (see Briggs et al. 1997).

Since GRO J1744−28 is located within a degree of the Galactic center, and its column density is very high, its distance is likely not much smaller than that of the Galactic center (7.5 kpc). Given the ±1 mag dispersion of individual sources around the average relation found by van Paradijs & McClintock (1994), we conclude from Table 1 that the expected *K* magnitudes of GRO J1744−28 are consistent with the observed upper limits.

J. G. is supported by the Deutsche Agentur für Raumfahrtangelegenheiten (DARA GmbH) under contract FKZ 50 OR 9201. The *ROSAT* project is supported by the Bundesministerium für Bildung, Wissenschaft, Forschung und Technologie (BMBW) and the Max-Planck-Society. J. v. P. is supported by NASA grant NAG 5-2755. W. H. G. L. is supported by NASA grant NAG 5-2046. C. K. is supported by NASA grant NAG 5-2560. P. D. B. is supported by NASA grant NAS 5-30720.

REFERENCES

Augusteijn, T., et al. 1996a, IAU Circ. 6326
———. 1996b, IAU Circ. 6369
Augusteijn, T., Lidman, C., & Blanco, P. 1996c, IAU Circ. 6484
Blanco, P., Lidman, C., & Glazebrook, K. 1996, IAU Circ. 6321
Borozdin, K., et al. 1996, IAU Circ. 6350
Bouchet, L., et al. 1996, IAU Circ. 6343
Briggs, M. S., et al. 1997, in preparation
Calla, O. P. N., et al. 1979, IAU Circ. 3347
Calla, O. P. N., Barathy, S., & Snagal, A. K. 1980a, IAU Circ. 3458
———. 1980b, IAU Circ. 3467
Cannizzo, J. 1996, ApJ, 466, L31
Cole, D. M., et al. 1996, IAU Circ. 6310
———. 1997, ApJ, 480, 377
Daumerie, P., et al. 1996, preprint
Dotani, T., et al. 1996a, IAU Circ. 6337
———. 1996b, IAU Circ. 6368
Finger, M. H., et al. 1996a, IAU Circ. 6284
Finger, M. H., Wilson, R. B., & van Paradijs, J. 1996b, IAU Circ. 6286
Finger, M. H., et al. 1996c, Nature 381, 291
Fishman, J. G., et al. 1995, IAU Circ. 6272
Frail, D. A., et al. 1996a, IAU Circ. 6307
———. 1996b, IAU Circ. 6323
Hurley, K., et al. 1995, IAU Circ. 6275
———. 1996, IAU Circ. 6286
Johnson, H. L. 1966, ARA&A, 4, 191
Jones, A. W., et al. 1980, Nature, 283, 550
Kommers, J., et al. 1996, IAU Circ. 6371
Kouveliotou, C., et al. 1996a, Nature, 379, 799
———. 1996b, IAU Circ. 6286
———. 1996c, IAU Circ. No, 6369
Kulkarni, P. V., et al. 1979, Nature, 280, 819
Lamb, D. Q., Miller, M. C., & Taam, R. E. 1996, preprint
Lawrence, A., et al. 1983, ApJ, 267, 301
Lewin, W. H. G., et al. 1976, ApJ, 207, L95
———. 1996, ApJ, 462, L39
Paciesas, W. S., et al. 1996, IAU Circ. 6284
Predehl, P., & Schmitt, J. H. M. M. 1995, A&A, 293, 889
Rieke, G. H., & Lebowski, M. J. 1985, ApJ, 288, 618
Stellingwerf, R. F. 1978, ApJ, 224, 953
Sturner, S. J., & Dermer, C. D. 1996, preprint
Swank, J. H., et al. 1996, IAU Circ. 6291
Vanden Berk, D. E., et al. 1996, IAU Circ. 6315
van Paradijs, J., et al. 1997, A&A, 317, L9
van Paradijs, J., & McClintock, J. E. 1994, A&A, 290, 131
———. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 58
Zimmermann, H. U., et al. 1994, EXSAS User's Guide (Rep. 257) (Garching: Max-Planck-Institut für extraterrestrische Physik)
Żytkow, A., & Irwin, M. 1996, IAU Circ. 6314