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POSSIBLE ASSOCIATION OF A QUIESCENT X-RAY SOURCE WITH A GAMMA-RAY BURSTER

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ABSTRACT

We report on the first repeatedly detected statistically significant coincidence (chance probability $\approx 10^{-2}$–10^{-3}) between an X-ray source and a gamma-ray burst error box. We present three *ROSAT* observations of the field of the gamma-ray burst of 1992 May 1. The first, a 2000 s target of opportunity observation, was carried out 18 days after the burst. A weak X-ray source was identified, but with too few photons to determine its spectral characteristics. The second, a 30 ks PSPC observation, resulted in the detection of 118 net photons over the 0.07–2.4 keV energy range. We find that the spectrum is consistent with thermal bremsstrahlung from a 7×10^6 K plasma with about 10^{22} cm^{-2} H I column density. The unabsorbed flux is $\sim 9.4 \times 10^{-13}$ ergs cm^{-2} s^{-1} (corresponding absorbed flux 4.8×10^{-14} ergs cm^{-2} s^{-1}). Analysis of the photon arrival times indicates that the source may be variable. Using the H I column density from the spectral fit, we set a lower limit to the source distance of at least several kpc; an extragalactic source cannot be ruled out. If the gamma-ray burst is indeed related to the X-ray source, its total energy output would have been at least 2×10^{37} ergs. The third observation, 6200 s with the HRI, defines a source error circle of 6″ radius. We discuss optical observations of this region, and consider various possibilities for the nature of the X-ray source.

Subject headings: gamma rays: bursts — X-rays: stars

1. INTRODUCTION

More than 20 years after their discovery, cosmic gamma-ray bursts (GRBs) remain one of the biggest mysteries in twentieth-century astronomy. Before the BATSE/CGRO era, it was generally believed that GRBs were associated with Galactic neutron stars, and it was expected that BATSE would confirm this paradigm. However, BATSE data have deepened the mystery. With over 1000 GRBs observed, the distribution can be shown to be highly isotropic (Briggs 1993), yet source-count statistics strongly suggest that BATSE has sampled to the edge of the GRB distribution (Fishman et al. 1994). On the basis of these data alone, very nearby, extended Galactic halo, cosmological models, or even combinations of the three cannot be ruled out. One of the most direct methods to reduce the large uncertainty in the distance scale is to identify a flaring, fading, or quiescent counterpart to a burst source in some other region of the electromagnetic spectrum. Unfortunately, previous searches in the radio, infrared, optical X-ray, and gamma-ray energy ranges have not identified any source which can be unambiguously proved to be associated with a classical GRB (Schaefer 1994). Most searches carried out to date have been for quiescent counterparts, and have yielded only upper limits to the counterpart intensity. Nevertheless, even an upper limit in an optical search is very useful for placing constraints on various GRB source models. For example, an "empty" error box can rule out an association between a GRB and a normal spiral galaxy or active galactic nucleus (AGN) host in cosmological models. The detection of a counterpart, on the other hand, would give information not only on the distance scale but also on the nature of the source. While some models of GRBs do not predict the presence of a detectable counterpart, it is encouraging to note the recent identification of the soft-gamma repeated SGR 1806−20 with an X-ray source and supernova remnant (Kouveliotou et al. 1994; Murakami et al. 1994; Kulkarni et al. 1994; Hurley et al. 1994a) and possibly with a luminous blue variable (van Kerkwijk et al. 1995), in addition to recent results supporting the well-known March 5/N49 association (Rothschild et al. 1994).

As noted by Owens, Schaefer, & Sembay (1995), *flaring* soft X-ray counterparts to burst sources are of particular interest due to the possibility of detecting absorption in their spectra. The soft X-rays will be absorbed by neutral hydrogen as they pass through their host galaxy and/or our own. Studying the column density traversed by a number of counterparts as a function of Galactic latitude provides a measure of the distance. In principle, this method can also work for quiescent soft X-ray counterparts. In addition, Klose (1994a, b) has pointed out that dust-scattering halos around quiescent soft X-ray sources can serve as distance indicators for burst sources. Previous searches for quiescent soft X-ray counterparts using the *Einstein* and *EXOSAT* spacecraft, however, have yielded only negative or ambiguous results (Grindlay et al. 1982; Pizzichini et al. 1986; Boer et al. 1988, 1991, 1993).

In this paper, we present recent soft X-ray observations of the 1992 May 1 GRB field using the *ROSAT* PSPC and

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HRI, and optical observations using the ESO 1.5 m Danish telescope. The *ROSAT* PSPC has a spatial resolution of ~25″ over a 2° field of view, and a spectral resolution of ~40% at 0.93 keV, over the 0.07–2.4 keV energy range. The HRI is a single-band imager with excellent spatial resolution. It covers roughly the same energy range as the PSPC, with a field of view of ~40′ and a central core FWHM of 1″.7. This is a factor of ~15 better than the PSPC, which facilitates the optical identification of any sources detected. For a description of the *ROSAT* mission and instrumentation, see Trümper (1983) and Pfefferman et al. (1986).

2. GAMMA-RAY AND X-RAY OBSERVATIONS

The 1992 May 1 GRB was observed by the Third Interplanetary Network (IPN), consisting at the time of *Ulysses* (GRB experiment: Hurley et al. 1992), the *Compton Gamma Ray Observatory* (BATSE: Fishman et al. 1992), and *Pioneer Venus Orbiter* (Klebesadel et al. 1980) missions. It lasted about 40 s, had a hard spectrum, a fluence of $\sim 2 \times 10^{-6}$ ergs cm^2, and a very striking, highly structured light curve (Fig. 1). A ~2 arcmin^2 error box was determined by triangulation.

2.1. PSPC *Observations*

On 1992 May 19 (18 days after the burst), a 2700 s *ROSAT* PSPC target of oportunity (ToO) observation of the position was carried out. The sensitivity of this observation was such that the minimum detectable source intensity was about 2.3×10^{-3} counts s^{-1}; this corresponds to $\sim 2.3 \times 10^{-13}$ ergs cm^{-2} s^{-1}, but the actual flux depends on the assumed spectral shape. Three sources were detected in the 2° field of view. A weak X-ray source was identified inside the GRB error box, but only 21 photons were collected, which is insufficient to determine the energy spectrum. The results of this observation, as well as of some initial radio and optical observations of the field, have been reported by Hurley et al. (1994b), Cline et al. (1994), and Palmer et al. (1995).

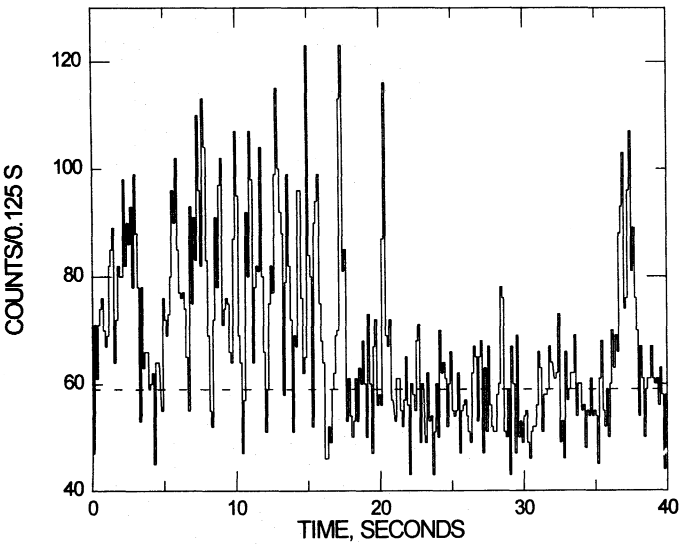

FIG. 1.—*Ulysses* 25–150 keV time history of GRB 920501. Dashed line indicates background level. At least 40 distinct peaks can be identified in the corresponding BATSE light curve, which has considerably better statistics.

In 1993 October, 1.4 yr after the burst, a 30 ks *ROSAT* PSPC observation was conducted to better determine the nature of this source. The minimum detectable source intensity was about 3×10^{-4} counts s^{-1} ($\sim 3 \times 10^{-14}$ ergs cm^{-2} s^{-1}). This deeper observation resulted in the collection of a total of 140 photons. Because of the longer observation time, 49 sources were identified in the field of view using the standard *ROSAT* source identification methods. Figure 2 (Plate 11) shows the portion of the image which contains most of the sources, along with the GRB error box. The X-ray source inside the error box is at $\alpha(2000) = 8^h15^m18^s.6$, $\delta(2000) = -32°44'28''.6$ ($l \sim 265°$, $b \sim 1°$). The counts are concentrated in a radius of about 22″, consistent with the PSPC point-spread function.

2.2. HRI *Observation*

On 1994 May 7 (2 yr after the burst), we carried out a 6200 s HRI observation of the GRB field (Fig. 3 [Pl. 12]). The sensitivity of this observation was such that the weakest detectable source intensity was 2.2×10^{-3} counts s^{-1} ($\sim 3.1 \times 10^{-12}$ ergs cm^{-2} s^{-1}, but, again, dependent on the assumed spectrum). Three sources were detected. Fourteen net photons were detected within the HRI error circle of the source described above. The best HRI position for the source is $\alpha(2000) = 08^h15^m18^s.06$, $\delta(2000) = -32°44'27''.02$. However, systematic errors of up to 10″ may exist at times in the absolute pointing accuracy of the HRI. Due to the better spatial resolution of the HRI, we find that the source counts are concentrated in an error circle whose 3 σ radius is 6″. Using the best-fit bremsstrahlung spectrum from the PSPC observation (see § 2.3), we find an unabsorbed flux $F_X = 3.1 \times 10^{-12}$ ergs cm^{-2} s^{-1}.

2.3. *Spectral Properties*

The energy spectrum of the source was analyzed by fitting the spectral data (118 net photons) with various models using XSPEC running under PROS/IRAF. Thirty-two channels were used, corresponding approximately to the energy range 0.1–2.4 keV. A power-law fit can be ruled out based on the large reduced χ^2 (2.43). The data are best fitted (reduced $\chi^2 = 0.93$) by a thermal bremsstrahlung function with a temperature $T = (7 \pm 1.1) \times 10^6$ K, plus absorption by Galactic neutral hydrogen with a column density $N_H = 10^{22 \pm 0.2}$ cm^{-2} (Fig. 4). Figure 5 shows the confidence intervals for T and N_H. A blackbody fit cannot be excluded; for $T = (3.2 \pm 1.1) \times 10^6$ K and $N_H = 10^{21.9 \pm 0.1}$ cm^{-2}, we obtain a reduced $\chi^2 = 0.94$. The total unabsorbed 0.1–2.4 keV flux is $F_X = 9.4 \times 10^{-13}$ ergs cm^{-2} s^{-1} for the bremsstrahlung fit. The corresponding absorbed flux is 4.8×10^{-14} ergs cm^{-2} s^{-1}. We note that a subsequent 0.5–10 keV *ASCA* observation of this source has revealed the presence of a power-law spectral component at energies above several keV (Murakami et al. 1996).

2.4. *Temporal Properties*

The hypothesis that the source is variable over short timescales (i.e., less than the observation time) has been tested for each of the three observations. In the initial ToO observation, a total of 21 photons were collected, and we have tested their arrival times for source variability using the Kolmogorov-Smirnov (K-S) test. The cumulative distribution function of the photon arrival times and of a hypothetical source with constant count rate (taken as the

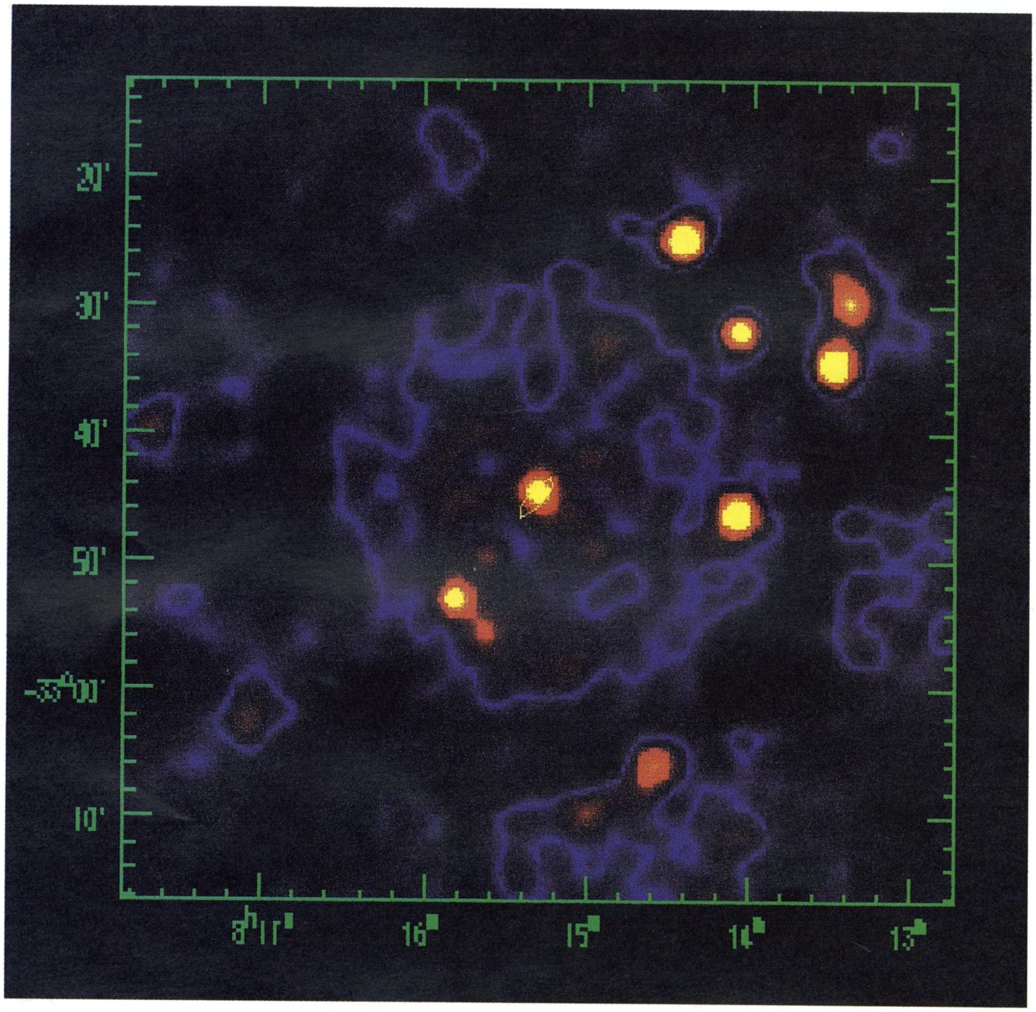

FIG. 2. Smoothed *ROSAT* PSPC image of the 1° × 1° field around the error box of GRB 920501. The total observation time was 30 ks. The GRB error box is indicated

HURLEY et al. (see 464, 343)

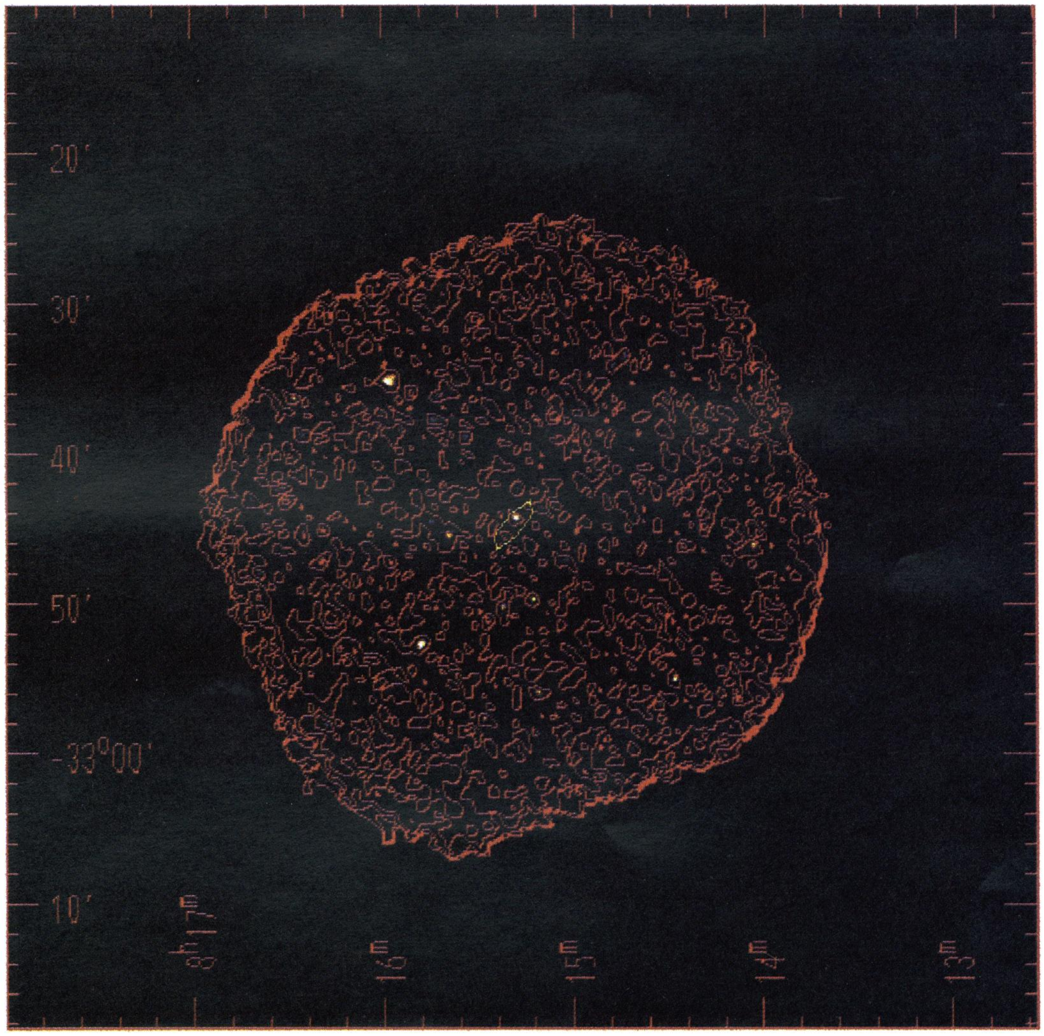

FIG. 3. Smoothed *ROSAT* HRI image of the 43′ × 43′ field of view around GRB 920501. The observation time was 6200 s. The GRB error box is also shown.

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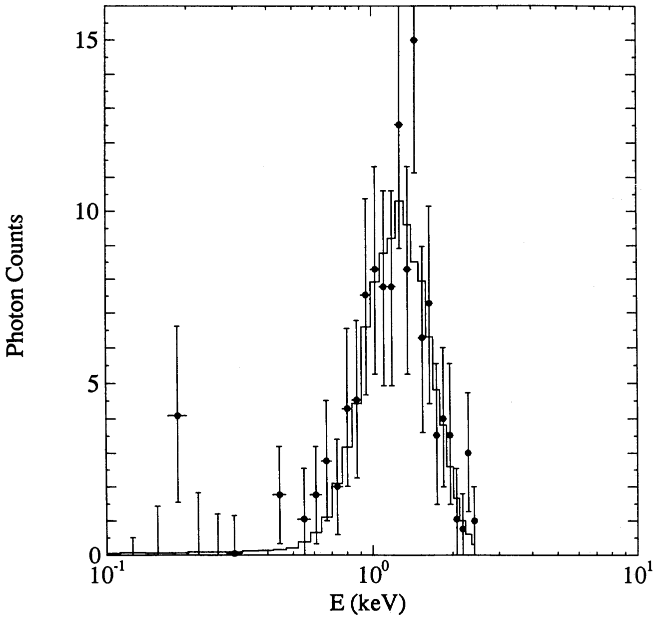

FIG. 4.—Observed count spectrum and the fitted thermal bremsstrahlung spectrum (reduced $\chi^2 = 0.9$) with H I absorption. The source temperature is $(7 \pm 1.1) \times 10^6$ K, and the H I column density is $N_{\rm H} = 10^{22 \pm 0.2}$ cm^{-2}.

mean of the observed source count rate) were compared. The two are consistent at only the 5% confidence level.

Figures 6*a* and 6*b* show the light curve of the X-ray source from the second PSPC observation; although a total of 30 ks was devoted to this observation and a total of 140 photons were recorded, the observation was punctuated by Earth occultations and other interruptions. A K-S test was again used to determine whether the photon arrival times were consistent with a steady source, after eliminating the gaps. The constant-source hypothesis is rejected at the 99% confidence level (see Fig. 7). Variability was also tested by binning the counts and calculating the χ^2 with respect to the average count rate. The result was $\chi^2 = 36.7$ for 11 degrees of freedom, or inconsistent with constancy at the 99.5% confidence level. We have also used the likelihood ratio test recommended by the Statistical Consulting Center for Astronomy (Rosenberger, Akritas, & Feigelson 1995). The result is inconsistent with constancy at the 93% confidence level. Finally, a K-S test on the arrival times of the 14 HRI photons indicates that the count rate is consistent with constancy at only the 1% confidence level.

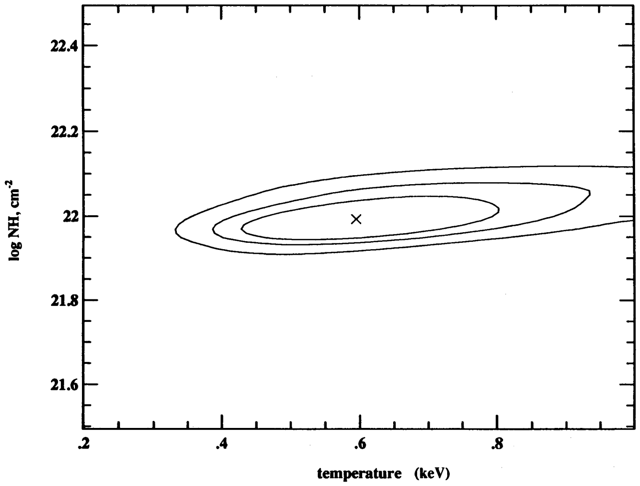

FIG. 5.—68%, 95%, and 99.7% confidence contours for the bremsstrahlung fit.

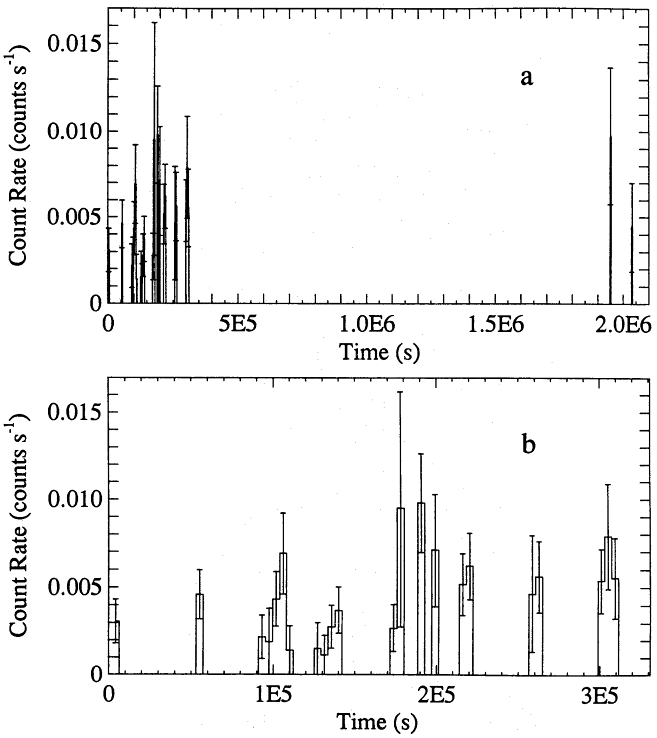

FIG. 6.—(*a*) Light curve of the X-ray source inside the GRB error box; (*b*) expanded view of the first observations. The time intervals are disjoint.

The hypothesis that the source is variable over longer timescales (i.e., from one observation to the next) has also been tested. As the ToO observation had too few photons to allow a reliable spectral deconvolution, and the HRI has

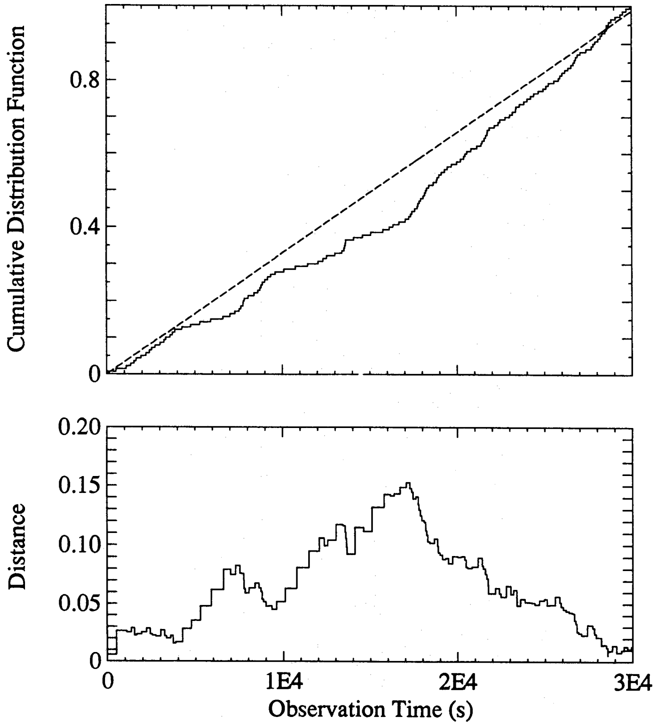

FIG. 7.—Kolmogorov-Smirnov test of the *ROSAT* source time history for the hypothesis of a constant source. In the upper panel, the solid line is the cumulative distribution function (cdf) of the source time history, and the dashed line is the cdf of a constant source. In the lower panel, the distance between these two distributions is shown; constancy is rejected at the 99% confidence level.

1996ApJ...464..342H

TABLE 1

PREVIOUS SOFT X-RAY COUNTERPART SEARCHES

Instrument	Energy Range (keV)	Sensitivity (10^{-13} ergs cm^{-2} s^{-1})	Number of Error Boxes Searched	Number of Sources Detected
Einstein[a]	0.5–0.3	1	1	1
Einstein[b]	0.1–4.5	0.93–115	5	0
EXOSAT[c]	0.02–2.5	2.4–14.3	2	0
EXOSAT[d]	0.02–2.5	430–3060	3	0
ROSAT (pointed)[e]	0.07–2.4	0.09–0.08	2	0
ROSAT (all-sky survey)[f]	0.1–2.4	~1	39	11
ROSAT (all-sky survey)[g]	0.1–2.4	~1	16	2
ROSAT WFC[h]	0.06–0.206	$\sim 10^{-11}$	12	0

[a] Grindlay et al. 1982.
[b] Pizzichini et al. 1986.
[c] Boer et al. 1988.
[d] Boer et al. 1991.
[e] Boer et al. 1993.
[f] Boer et al. 1994a.
[g] Boer et al. 1994b.
[h] Owens et al. 1993.

no spectral resolution, we assume that the source may be characterized by the best-fitting PSPC spectrum. Then the ToO observation gives a flux $(8.0 \pm 2.6) \times 10^{-13}$ ergs cm^{-2} s^{-1}, while the HRI observation gives a flux $(3.1 \pm 1.0) \times 10^{-12}$ ergs cm^{-2} s^{-1}. These may be compared to the PSPC flux of $(9.4 \pm 3.1) \times 10^{-13}$ ergs cm^{-2} s^{-1}. The differences between these three observations are significant at less than the 2 σ level, so the evidence for long-term variability is not strong.

3. PROBABILITIES

Key to the question of whether this X-ray source is indeed associated with the gamma-ray burst source is the probability of a random coincidence. There are numerous ways to pose the problem, which we now review.

1. What is the probability that, in the ToO observation, exactly one of the sources detected has a position consistent with the error box? The sources may be approximated by circles of radii $r = 0'.37$ (FWHM); if we approximate the 2 arcmin^2 GRB error box by a circle of radius $R = 0'.8$, we can define a circle with radius $r + R$, consider the *ROSAT* sources to be points, and ask what the probability is of one point falling within the larger circle. For a field of view of radius $R_F = 60'$, this is $3(r + R)^2/R_F^2 = 1.1 \times 10^{-3}$.

2. What is the probability that, in the deeper PSPC observation, exactly one of the sources detected has a position consistent with the error box? By the same reasoning as above, we obtain $49(r + R)^2/R_F^2 = 5.9 \times 10^{-2}$.

3. What is the probability that a 2 arcmin^2 error box, anywhere in the Galactic plane, will contain an X-ray source? There are about 10,000 sources located at $|b| < 20°$ in the WGA catalog (White, Giommi, & Angelini 1995), or 1.12×10^{-3} sources arcmin^2. If the sources are approximated by points, the probability that a 2 arcmin^2 error box contains a source is approximately 2.2×10^{-3}. This estimate makes no correction for the sky exposure as a function of Galactic latitude, and encompasses the widely varying sensitivities of the *ROSAT* pointed observations in the public domain (typical observation times 5000–30,000 s).

4. How many attempts have been made to find an X-ray counterpart to a GRB source, what were their sensitivities, and what were the results? Table 1 summarizes the previous searches; note, however, that this includes a wide variety of energy ranges, error box sizes, probabilities of chance detection, and sensitivities, the latter calculated under varying assumptions concerning the spectrum. In particular, the *ROSAT* sky survey searches included very large error boxes, with correspondingly large probabilities of chance occurrences. Finally Table 1 includes multiple observations of some error boxes.

A more accurate answer to this question is given in Table 2, which lists the total number of error boxes searched to various sensitivities. Here, only the single most sensitive observation of a given error box is considered, and the soft-gamma repeater observations have been eliminated, since these are all known or strongly suspected to have soft X-ray counterparts. From this table, the number of previous searches which would have detected the present source may be estimated at three, and none of these revealed any source. In a frequentist calculation, probabilities 1–3 above would have been increased by this factor.

5. Is it more probable to find a variable or a steady source? Roughly 1% of the sources in the WGA catalog are classified as variable (P. Giommi 1995, private communication). In this catalog, the variable sources tend to be late-type and pre–main-sequence stars, CVs, X-ray binaries, AGNs, and as yet unclassified sources. Extended Galactic objects, OB stars, clusters, and most galaxies tend to be steady sources. Thus, if the evidence for variability of this source is accepted, the probability of finding this type of source is approximately 100 times less than the probability of finding a steady source.

TABLE 2

SOFT X-RAY SEARCHES ORDERED BY SENSITIVITY

Sensitivity (10^{-13} ergs cm^{-2} s^{-1})	Number of Error Boxes Searched to this Sensitivity or Less
0.08	56
0.09	55
0.7	54
~1	53
900	1

4. OPTICAL OBSERVATIONS

CCD observations of this region were carried out at the 1.5 m Danish telescope at ESO/La Silla 12 days after the burst. We obtained 300 s *R*, *B*, and *U* frames. Figure 8 (Plate 13) shows the *R*-band image with the GRB error box and the HRI X-ray source circle superimposed. Figure 9 (Plate 14) is an enlargement of the HRI region in the three bands. There is only one optical source inside the HRI error circle. Subsequent deeper observations have been carried out over the years at Mount Palomar (R. Romani 1995, private communication), at CTIO (B. Schaefer 1995, private communication), and at USNO (F. Vrba 1995, private communication); we have recently carried out Keck observations of this region. When the stellar type of the object in Figure 9 has been determined, it should be possible, using the well-known relation between X-ray absorption and optical extinction (e.g., Gorenstein 1975), to determine whether it is at the same distance as the X-ray source, and thus whether it is a likely optical counterpart to it.

5. SOURCE DISTANCE AND POSSIBLE NATURE

The total Galactic H I column density in the direction of the X-ray source is greater than 5.6×10^{21} cm^{-2} (J. Lockman 1995, private communication), which is within a factor of 2 the column density deduced from the spectral fit, and probably not inconsistent with it, considering the uncertainties. Taking a rough average of 1 atom cm^{-3}, the source distance may be estimated at 1.6–3 kpc. At a Galactic longitude of 265°, the distance of the source from the Galactic center can be estimated at 9 kpc; however, the optical observations in this direction indicate a very patchy interstellar medium (an anonymous galaxy is clearly detected within several arcminutes of the X-ray source; see Fig. 8), so an extragalactic source cannot be excluded. The low Galactic latitude argues against, but does not rule out, this possibility. In principle, since this source lies in the direction of the Galactic plane, measurement of its dust scattering X-ray halo could help confirm its distance (Predehl & Schmitt 1995; Klose 1994a, b). However, a distance through the dust layer of only several kiloparsecs leads to scattering optical depths of several tenths, and the number of photons collected in our observations is too small to allow the detection of the resulting halo.

If we assume that the source is Galactic, and at a distance of 3 kpc, its luminosity is

$$L_X = 4\pi d^2 F_X = 10^{33} \text{ ergs s}^{-1} . \qquad (1)$$

Could this be coronal emission from a random field star? The luminosity is considerably higher than that of dwarf stars, which are typically in the range 10^{26}–10^{31} ergs s^{-1} (e.g., Rosner, Golub, & Vaiana 1985). Similarly, it is higher than the luminosities of RS CVn systems (typically, 10^{29}–$10^{31.5}$ ergs s^{-1}; Dempsey et al. 1995). Stars earlier than B5 are all X-ray emitters at levels between 10^{29} and 10^{34} ergs s^{-1}, but, while their temperatures are $\sim 10^7$ K, their X-ray to bolometric luminosity ratios are around $\sim 10^{-7}$ (Rosner, Golub, & Vaiana 1985; Harnden et al. 1979; Seward et al. 1979). If the optical object in the error circle of this source is the counterpart, its bolometric luminosity may be estimated as follows. Its apparent *V* magnitude is $\sim$18.5 (C. Luginbuhl 1995, private communication); an average extinction is $A_V = 1.9$ mag kpc^{-1} (Allen 1976), so at a distance of 3 kpc, $m_V \approx 12.8$. Bolometric corrections for normal stars range from about 0 to -4 (Allen 1976). Thus the flux of this star is $\sim 1.2 \times 10^{-9}$ ergs cm^{-2} s^{-1}. We get $L_X/L_{\rm opt} \approx 6 \times 10^{-5}$, with an uncertainty of a factor of 6 due to the bolometric correction. Even with the large uncertainty inherent in this ratio, this suggests that if this object is the optical counterpart, it is not an early-type star.

Another possible explanation is an X-ray binary containing a neutron star. If this is the case, the X-ray luminosity is

$$L_X \approx \epsilon \frac{M_X G \dot{M}_a}{R} = 8.4 \times 10^{44} \frac{M_X \dot{M}_a}{R} \text{ ergs s}^{-1} , \qquad (2)$$

where M_X and R are the mass and radius of the secondary, $\dot{M}_a$ is the mass accretion rate, and ϵ is the conversion efficiency of the accretion energy to radiation in X-rays, assumed to be 10%. Here M_X is in $M_\odot$, $\dot{M}_a$ is in $M_\odot$ yr^{-1}, and R is in units of 10 km. Using typical values for a neutron star binary, $M_X = 1.2\, M_\odot$, and $R = 10$ km, gives

$$\dot{M}_a = 9.92 \times 10^{-13} \, M_\odot \text{ yr}^{-1} . \qquad (3)$$

This mass-loss rate is lower than that of typical X-ray binaries, suggesting that the source may be in a quiescent state.

Alternatively, we can use the blackbody spectral fit to get a relation between the size of the emitting region and the mass accretion rate. If the accretion energy is completely thermalized and the neutron star surface radiates as a blackbody, we have

$$\sigma T^4 = \frac{G M_X \dot{M}_a}{RA} \qquad (4)$$

where σ is the Stefan-Boltzmann constant, T is the temperature at the neutron star surface, and A is the emitting area. T is related to the observed temperature T_∞ through $T_\infty = T(1+z)^{-1}$, where $(1+z) = [(1–2) \times (GM_X)/(c^2 R)]^{-1/2}$. Thus the accretion rate is given by

$$\dot{M}_a = \frac{R\sigma}{GM_X} (1+z)^4 T_\infty^4 A . \qquad (5)$$

Using the blackbody temperature from the spectral fit ($T_\infty = 3.2 \times 10^6$ K), we have

$$\dot{M}_a = 1.68 \times 10^{-14} A . \qquad (6)$$

If the emitting area is taken to be the entire surface, we obtain 2.1×10^{-11} $M_\odot$ yr^{-1}. If it is taken to be a 1 km radius polar cap, we obtain 5.3×10^{-14} $M_\odot$ yr^{-1}. In both cases, the accretion rates are low.

6. DISCUSSION AND CONCLUSION

We have presented evidence for the first repeatedly detected, statistically significant coincidence of an X-ray source and a GRB error box. This X-ray source probably lies at a distance of at least several kiloparsecs, based on the neutral hydrogen column density and extinction in this direction. The probability of a chance association between such a source and a GRB error box is between $\sim 10^{-2}$ and $\sim 10^{-3}$, depending upon the exact hypothesis tested. Neither the nature of the X-ray source nor the relation between it and the optical object is clear at present. We have recently conducted Keck observations which should lead to a better understanding of the true optical counterpart. If its nature is sufficiently unusual to warrant associating it and

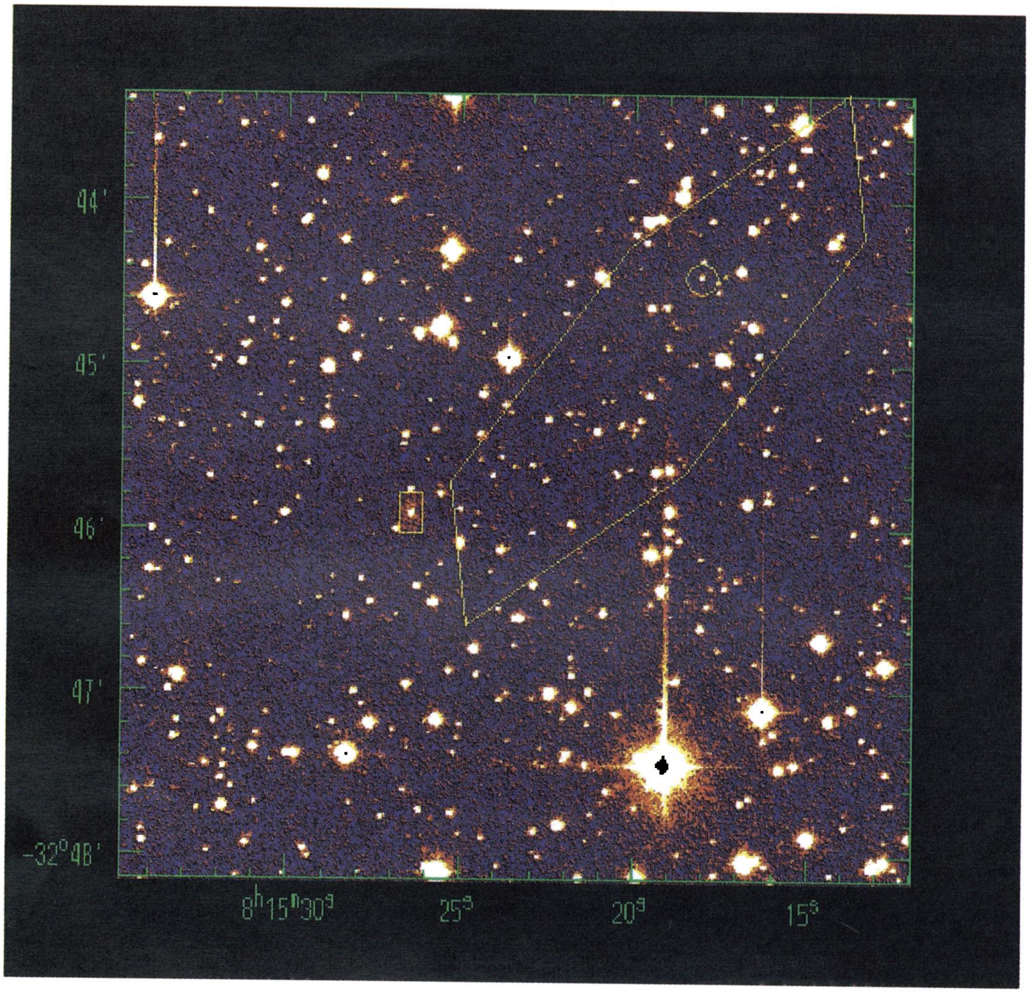

FIG. 8. GRB error box and the HRI X-ray source error circle (6″ radius) overlaid on the *R*-band CCD image from the 1.5 m Danish telescope. The limiting magnitude is about 20. The small rectangle indicates the position of a galaxy.

HURLEY et al. (see 464, 346)

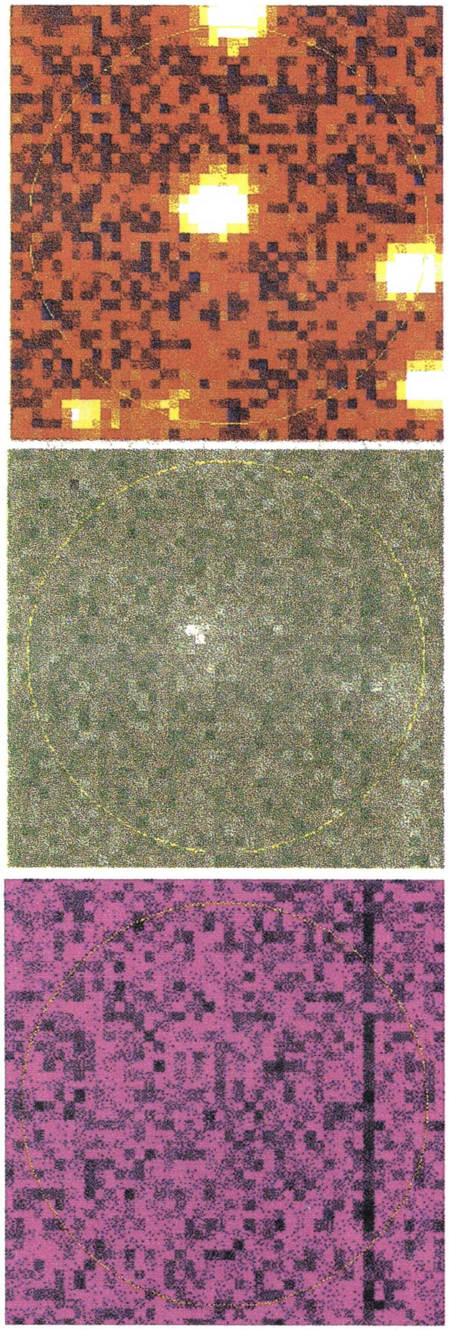

FIG. 9. CCD *R*, *B*, and *U* images of the region inside the HRI error circle, centered at $\alpha(2000) = 8^{h}15^{m}18^{s}.06$, $\delta(2000) = -32°44'27''.04$. The field of view is $5' \times 5'$. The observing conditions were not photometric, but the *R* and *B* magnitudes are estimated at 18.4 ± 0.1 and 19.9 ± 0.3, respectively. Observations stopped after the *U* frame due to clouds, making the calibration of this observation uncertain.

HURLEY et al. (see 464, 346)

the X-ray source with the source of GRB 920501, then at least one GRB source will have been shown to be Galactic, although this would be far from a demonstration that all are. Heliospheric and extragalactic models might still be needed to explain the great diversity of burst properties. In any case, however, experience gained from previous counterpart searches teaches us that it is not a trivial task to establish such a connection. At this point, we stress that an association may only be argued on statistical grounds. It is a curious fact that the three previous X-ray counterpart searches which reached sensitivity levels sufficient to detect a source such as the one in this error box failed to do so, even though the gamma-ray bursts associated with those searches were of comparable or greater fluence than GRB 920501.

The lesson of the March 5/N49 association is that any proposed GRB counterpart will remain controversial until a second or third identification provides supporting evidence. Such evidence may eventually come from deep counterpart searches of future IPN precise localizations, or of the GRB positions that the *High Energy Transient Experiment* (*HETE*) will downlink to Earth in near real time, if it succeeds in detecting flaring counterparts following its launch later this year.

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REFERENCES

Allen, C. 1976, Astrophysical Quantities (London: Athlone)
Boer, M., et al. 1988, A&A, 202, 117
Boer, M., Greiner, J., Kahabka, P., Motch, C., & Voges, W. 1994a, in AIP Conf. Proc. 307, Gamma-Ray Bursts, Second Workshop, ed. G. Fishman, J. Brainerd, & K. Hurley (New York: AIP), 453
Boer, M., et al. 1994b, in AIP Conf. Proc. 307, Gamma-Ray Bursts, Second Workshop, ed. G. Fishman, J. Brainerd, & K. Hurley (New York: AIP), 458
Boer, M., Hurley, K., Pizzichini, G., & Gottardi, M. 1991, A&A, 249, 118
Boer, M., Pizzichini, G., Hartmann, D., Hurley, K., Kouveliotou, C., & Motch, C. 1993, A&A, 277, 503
Briggs, M. 1993, ApJ, 407, 126
Cline, T., et al. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts Second Workshop, ed. G. Fishman, J. Brainerd, & K. Hurley (New York: AIP), 373
Dempsey, R., Linsky, J., Fleming, T., & Schmitt, J. 1995, ApJS, 86, 599
Fishman, G. J., et al. 1992, in AIP Conf. Proc. 265, Gamma-Ray Bursts, ed. W. Paciesas & G. J. Fishman (New York: AIP), 13
———. 1994, ApJS, 92, 229
Gorenstein, P. 1975, ApJ, 198, 95
Grindlay, J., et al. 1982, Nature, 300, 730
Harnden, R., et al. 1979, ApJ, 234, L51
Hurley, K., et al. 1992, A&AS, 92, 401
———. 1994a, ApJ, 431, L31
———. 1994b, ApJS, 92, 655
Klebesadel, R., Evans, W., Glore, J., Spalding, R., & Wymer, F. 1980, IEEE Trans. Geoscience & Remote Sensing GE-18, 1
Klose, S. 1994a, ApJ, 423, L23
———. 1994b, A&A, 289, L1
Kouveliotou, C., et al. 1994, Nature, 368, 125
Kulkarni, S., et al. 1994, Nature, 368, 129
Murakami, T., et al. 1994, Nature, 368, 127
———. 1996, PASJ, in press
Owens, A., Schaefer, B., & Sembay, S. 1995, ApJ, 447, 279
Owens, A., Sembay, S., Sims, M., Wells, A., & Schaefer, B. 1993, in AIP Conf. Proc. 280, *Compton Gamma Ray Observatory*, ed. M. Friedlander, N. Gehrels, & D. Macomb (New York: AIP), 798
Palmer, D., Cline, T., Laros, J., Hurley, K., Fishman, G., & Kouveliotou, C. 1995, in Proc. 29th ESLAB Symp., Towards the Source of Gamma-Ray Bursts (Ap&SS, Vol. 231), 315
Pfefferman, E., et al. 1986, Proc. SPIE, 733, 519
Pizzichini, G., et al. 1986, ApJ, 301, 641
Predehl, P., & Schmitt, J. 1995, A&A, 293, 889
Rosenberger, J., Akritas, M., & Feigelson, E. 1995, Twenty Questions and Answers from the Statistical Consulting Center for Astronomy, Statistical Consulting Center for Astronomy, Department of Statistics, Pennsylvania State Univ.
Rosner, R., Golub, L., & Vaiana, G. 1985, ARA&A, 23, 412
Rothschild, R., et al. 1994, Nature, 368, 432
Schaefer, B. 1994, in AIP Conf. Proc. 307, Gamma-Ray Bursts, Second Workshop, ed. G. Fishman, J. Brainerd, & K. Hurley (New York: AIP), 382
Seward, F., et al. 1979, ApJ, 234, L55
Trümper, J. 1983, Adv. Space Res., 2(4), 241
van Kerkwijk, M., Kulkarni, S., Matthews, K., & Neugebauer, G. 1995, ApJ, 444, L33
White, N., Giommi, P., & Angelini, L. 1995, The WGA Catalog of *ROSAT* Point Sources (available on line through the HEASARC) (http://legacy.gsfc.nasa.gov/~white/wgacat/head.html)