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PRECISE INTERPLANETARY NETWORK LOCALIZATION OF THE BURSTING PULSAR GRO J1744−28

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ABSTRACT

We analyze 426 observations of the bursting pulsar GRO J1744−28 by *Ulysses* and BATSE. Triangulating each burst and statistically combining the triangulation annuli, we obtain a 3 σ error ellipse whose area is 532 arcsec^2. The accuracy of this statistical method has been independently verified with observations of the soft gamma repeater SGR 1900+14. The ellipse is fully contained within the 1′ radius *ASCA* error circle of the soft X-ray counterpart and partially overlaps the 10″ radius *ROSAT* error circle of a source which may also be the soft X-ray counterpart. A variable source which has been proposed as a possible IR counterpart lies at the edge of the 3 σ error ellipse, making it unlikely from a purely statistical point of view to be associated with the bursting pulsar.

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

1. INTRODUCTION

The bursting pulsar GRO J1744−28 was discovered with the Burst and Transient Source Experiment (BATSE) aboard the *Compton Gamma-Ray Observatory* (*CGRO*) in 1995 December (Fishman et al. 1995; Kouveliotou et al. 1996a). Between the discovery date and 1997 April, BATSE detected over 5800 type II bursts (i.e., accretion-powered; Lewin et al. 1996) from this source (Woods et al. 1999), many of which were also detected by instruments aboard the *Rossi X-Ray Timing Explorer* (*RXTE*: Giles et al. 1996) and *Ulysses* among others (e.g., Konus-WIND: Aptekar et al. 1998). The initial source localization was a 6° radius error circle (Fishman et al. 1995). Triangulation with BATSE and *Ulysses* resulted in a 24′ wide annulus which intersected this error circle, and the use of the BATSE Earth occultation technique reduced the area of the localization further (Hurley et al. 1995). Observations using the Oriented Scintillation Spectrometer Experiment (Kurfess et al. 1995; Strickman et al. 1996) and BATSE observations of a variable, pulsating (467 ms period) quiescent source associated with the bursting source (Finger et al. 1996a, 1996b; Paciesas et al. 1996) resulted in a still smaller error box. A subsequent *RXTE* observation produced an $\approx$5 arcmin^2 error box (Swank 1996; Giles et al. 1996). Within this error box, Frail et al. (1996a, 1996b) found a variable radio source. Observations of the region around the radio source position with the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) revealed a pulsating, bursting X-ray source with the same 467 ms period (Dotani et al. 1996a, 1996b) whose position was consistent with that of the radio source, but a later *ROSAT* observation (Kouveliotou et al. 1996b; Augusteijn et al. 1997) with higher angular resolution found an X-ray source within the 1′ radius *ASCA* error circle which was significantly displaced from the radio position. The radius of the *ROSAT* error circle is 10″, corresponding to a 5″ statistical error and a 8″ systematic error, summed in quadrature. No confidence level can be quoted for the systematic error, but the statistical error corresponds to $\sim$10 σ (J. Greiner 1999, private communication).

Although the radio source was rejected as a possible counterpart to GRO J1744−28, optical and near-infrared observations of the *ROSAT* source region did uncover an object at the limit of the 10″ radius *ROSAT* error circle which appeared to be variable (Augusteijn et al. 1997; Cole et al. 1997). These observations were carried out at the European Southern Observatory (ESO) and at the Astrophysical Research Consortium's Apache Point Observatory

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(APO). In some of the observations, it was not possible to rule out the apparent detection as an instrumental artifact (Augusteijn et al. 1997); in others, however, there was no reason to suspect that the detection was not valid (Cole et al. 1997).

It has been proposed that GRO J1744−28 is a low-mass X-ray binary system (LMXB), in which a neutron star with a dipole field $B \lesssim 10^{11}$ G accretes matter from its companion. The rotation period of the neutron star is 467 ms, the orbital period of the system is 11.8 days, and the system is viewed nearly face-on (e.g., Daumerie et al. 1996). The distance is approximately that of the Galactic center.

Because of the difficulty of identifying the counterpart at various wavelengths in a crowded region of the sky toward the Galactic center, it is important to consider the details of the *ROSAT* observation. It was a short one (820 s) with the High Resolution Imager (HRI); only 273 photons were collected, and, in contrast to the *ASCA* observation, neither pulsations nor bursts were detected. (During the observation, no bursts were recorded by BATSE or *Ulysses* either, and the upper limit to the *ROSAT* pulsed flux is consistent with that derived from BATSE and *RXTE* observations.) From earlier *ROSAT* observations in which the source was not detected, it was concluded that the object was transient; based on the statistics of transient sources in the Galactic plane, it was estimated that the probability of observing a random source unrelated to the bursting pulsar was less than 10^{-4}. Since no energy spectra are recorded by the HRI, the *ASCA* spectrum was assumed to calculate the source flux; it was found to be $\approx 2 \times 10^{-9}$ ergs cm^{-2} s^{-1} (unabsorbed) in the 0.1–2.4 keV energy range (Augusteijn et al. 1997). This observation took place in 1996 March. For comparison, the fluxes measured by *ASCA* in the 2–10 keV energy range were 2×10^{-8} ergs cm^{-2} s^{-1} in 1996 February and 5×10^{-9} ergs cm^{-2} s^{-1} in 1997 March (Nishiuchi et al. 1999). These fluxes would convert to unabsorbed 0.1–2.4 keV fluxes of 9.7×10^{-9} ergs cm^{-2} s^{-1} and 2.4×10^{-9} ergs cm^{-2} s^{-1}, respectively, using a simple extrapolation of the power-law continuum measured by Nishiuchi et al. (1999).

To summarize, there are good arguments both in favor of and against the idea that the true X-ray and optical/IR counterparts to GRO J1744−28 have been identified. In favor:

1. This was the only *ROSAT* source detected within the *ASCA* error circle,
2. It was transient, and
3. The variable optical/IR source was reliably detected in some of the observations of Cole et al. (1997).

Against:

1. No bursts or pulsations were observed by *ROSAT* (although the short duration of the observation may be to blame);
2. Augusteijn et al. (1997) estimate that the proposed optical/IR counterpart, if real, exhibited a change in its IR flux by a factor of 10 over a period of minutes, with no accompanying X-radiation; the detection could have been an artifact; and
3. The proposed optical/IR counterpart lies at the edge of or just outside the *ROSAT* error circle (depending on the astrometry).

Here we adopt the view that the true counterpart to GRO J1744−28 may not yet have been identified and localized with certainty, and we analyze the observations of bursts from GRO J1744−28 by *Ulysses* and BATSE in order to better constrain the position of the source.

2. OBSERVATIONS

We began this analysis by examining *Ulysses* gamma-ray burst (GRB) experiment (Hurley et al. 1992) data for each BATSE burst. Knowing the arrival time of a burst at BATSE, the coordinates of the *Ulysses* spacecraft, and the approximate source position, we extracted data for $\sim \pm 100$ s about the *Ulysses* crossing time. Although the bursting pulsar was a prolific source, it was not a particularly intense one, and this procedure resulted in the identification of only ≈ 500 bursts in the *Ulysses* data. Typically, these were count rate increases in the 3–6 σ range. The vast majority of them were recorded in the untriggered data, which have a time resolution of 0.25–2 s, depending on the telemetry mode. We then retained only those bursts which were recorded by BATSE with 0.064 s time resolution, since these are the ones which can be cross-correlated with the *Ulysses* time histories with the best accuracy. Figure 1 shows one example. The final data set then consisted of 426 bursts, of which only five were recorded by *Ulysses* in triggered (32 ms resolution) data. The first event in this set was BATSE 4042 on 1995 December 19, and the last was BATSE 6085 on 1997 February 2.

Triangulation of a single burst results in an annulus of possible arrival directions whose width depends on the vector between the two spacecraft and the uncertainty in cross-correlating the two time histories (see, e.g., Hurley et al. 1999a). As examples, we show the first and last annuli in Figure 2. Their widths are $\approx 0\farcm9$ and $3\farcm8$ (1 σ), respectively, and they intersect at an angle $\approx 37°$, approximately the same angle as the displacement of the Earth-*Ulysses* vector during the period between the bursts. In Figure 3 we show

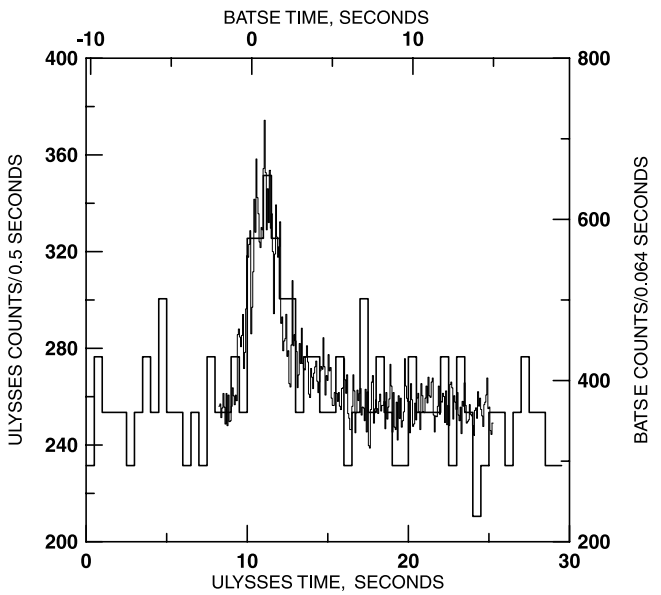

FIG. 1.—*Ulysses* (thick line) and BATSE (thin line) time histories for trigger 4317. The *Ulysses* time resolution is 0.5 s, and the data are for the 25–150 keV energy range. The BATSE time resolution is 0.064 s, and the data are for the 25–100 keV energy range. The time histories are aligned for the best-fitting lag.