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ABSTRACT

We apply a statistical method to derive very precise locations for soft gamma repeaters using data from the interplanetary network. We demonstrate the validity of the method by deriving a 600 arcsec^2 error ellipse for SGR 1900+14 whose center agrees well with the VLA source position. We then apply it to SGR 1806−20, for which we obtain a 230 arcsec^2 error ellipse, the smallest burst error box to date. We find that the most likely position of the source has a small but significant displacement from that of the nonthermal core of the radio supernova remnant G10.0-0.3, which was previously thought to be the position of the repeater. We propose a different model to explain the changing supernova remnant morphology and the positions of the luminous blue variable and the bursting source.

Subject headings: gamma rays: bursts — stars: neutron — supernova remnants — X-rays: stars

1. INTRODUCTION

The four known soft gamma repeaters (SGRs) are neutron stars in or near radio or optical supernova remnants. SGR 1806−20 was discovered in 1986 (Laros et al. 1986) and underwent a period of intense activity in 1987 (Laros et al. 1987; Kouveliotou et al. 1987), which led to its localization to an ∼400 arcmin^2 error ellipse (Atteia et al. 1987). Based on this position, Kulkarni & Frail (1993) suggested that the SGR was associated with the Galactic radio supernova remnant (SNR) G10.0-0.3. This was confirmed when the *Advanced Satellite for Cosmology and Astrophysics* (*ASCA*) observed and imaged the source in outburst, leading to an ∼1′ radius error circle (Murakami et al. 1994). *ROSAT* observations of the quiescent X-ray source associated with SGR 1806−20 confirmed the *ASCA* data (Cooke 1993; Cooke et al. 1993). It is believed that the SGRs are "magnetars," i.e., single neutron stars in which the magnetic field energy dominates all other sources of energy, including rotation (Duncan & Thompson 1992). In the case of SGR 1806−20, evidence for this model comes from observations of the period and period derivative of the quiescent soft X-ray emission (Kouveliotou et al. 1998).

Studies of the radio nebula show evidence for changes in its morphology on ∼1 yr timescales and suggest that the neutron star may be located at the nonthermal core of the radio emission (Frail, Vasisht, & Kulkarni 1997). The position of the core also coincides with that of an unusual star, which is identified as a luminous blue variable (LBV) by van Kerkwijk et al. (1995). This appears to be the only case so far of an SGR with an optical stellar counterpart, and the connection between this object and the SGR has been unclear up to now.

SGR 1806−20 has remained active over the past several

years, and many bursts have been detected by the Interplanetary Network (IPN), consisting primarily in this case of BATSE, *Ulysses*, and KONUS-*Wind*. However, only eight events have been intense enough to trigger both *Ulysses* and a near-Earth spacecraft, resulting in high time resolution data (the other bursts were recorded with lower time resolution by one or more instruments). It is these triggered events that lead to the most precise determination of the source position by triangulation.

2. OBSERVATIONS

Details of the eight triggered bursts are given in Table 1. In each case, triangulation using *Ulysses* and either BATSE or KONUS results in a single annulus with a width of ∼23″–28″, which defines the possible arrival direction for the burst. Two such annuli define an error box, if the angular separation between their centers is sufficient to prevent the annuli from intersecting at grazing incidence. Over the ∼2 yr period analyzed here, the *Ulysses*-Earth vector moved sufficiently to define a nondegenerate error box. With three or more annuli, the problem of defining the source location becomes overdetermined, and we can use a statistical method to derive the most probable source location. This consists of defining a χ^2 that is a function of an assumed source position in right ascension and declination and of the parameters describing the eight annuli. Let α and δ be the right ascension and declination of the assumed source position, and let α_i, δ_i, and θ_i be the right ascension, declination, and radius of the ith annulus. Then the angular distance d_i between the two is given by

$$d_i = \theta_i - \cos^{-1}\left[\sin(\delta)\sin(\delta_i) + \cos(\delta)\cos(\delta_i)\cos(\alpha - \alpha_i)\right].$$

(1)

If the 1 σ uncertainty in the annulus width is σ_i, then

$$\chi^2 = \sum_i \frac{d_i^2}{\sigma_i^2}.$$

(2)

The assumed source position is varied to obtain a minimum

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| | | ANNULUS CENTER | | | 3 σ |
DATE	UT (s)	α(2000) (deg)	δ(2000) (deg)	RADIUS, θ (deg)	HALF-WIDTH (deg)
1996 Nov 19	19826	358.8945	−30.9318	76.9907	0.0031
1996 Dec 30	65965	359.0677	−32.4563	76.7108	0.0035
1997 Jan 24	28043	355.4360	−34.4572	73.2710	0.0038
1997 Apr 14	39219	334.4596	−34.6283	56.1701	0.0039
1997 Aug 27	06045	341.3113	−19.3428	64.5125	0.0026
1997 Sep 02	39347	342.2306	−18.6910	65.5168	0.0026
1998 Aug 05	37673	335.3991	−06.2919	62.7583	0.0026
1999 Feb 05	31452	341.2378	+09.8529	74.3287	0.0035

χ^2; 1, 2, and 3 σ equivalent confidence contours in α and δ are found by increasing χ^2_{min} by 2.3, 6.2, and 11.8.

We have tested this method on six IPN annuli for SGR 1900+14 (Table 2), whose precise (subarcsecond) location is known from VLA observations of a particle outburst (Frail, Kulkarni, & Bloom 1999) following the giant flare of 1998 August 27 (Hurley et al. 1999a). The result is shown in Figure 1. The 3 σ error ellipse has an area of ~600 arcsec², and the best-fitting position for the SGR, at α(2000) = 19ʰ07ᵐ14ˢ3, δ(2000) = 9°19′19″, has a χ^2 of 1.05 for 4 degrees of freedom (dof) (six annuli minus the two fitting parameters α and δ). It lies ~0″6 from the VLA position.

The results of applying the method to SGR 1806−20 are shown in Figure 2. The best-fit position is at α(2000) = 18ʰ08ᵐ39ˢ4, δ(2000) = −20°24′38.6″, with a χ^2 of 3.35 for 6 dof (eight annuli minus two fitting parameters). It lies ~15″ from the center of the nonthermal core and well outside it. The 3 σ error ellipse has an area of ~230 arcsec², making it the smallest burst error box determined to date (the 324 arcsec² error box of the 1979 March 5 burst was, until now, "the most precisely determined gamma-ray source error box in existence" [Cline et al. 1982]). The position of the nonthermal core has a total χ^2 of 101.

3. ACCURACY OF THE METHOD

Since each individual annulus gives, in effect, an underdetermined source position, it is possible in principle that unknown systematic errors might affect the location accuracy. For example, timing errors of 96–206 ms in the *Ulysses* data could shift the positions of the annuli by different amounts and make them all consistent with that of the nonthermal core. Apart from the unlikely combination of errors that this would require (i.e., each annulus would have to be subject to a different error in such a way as to make the erroneous best-fit position have an acceptable χ^2), there are several independent confirmations of the accuracy of the triangulation method. The first is the
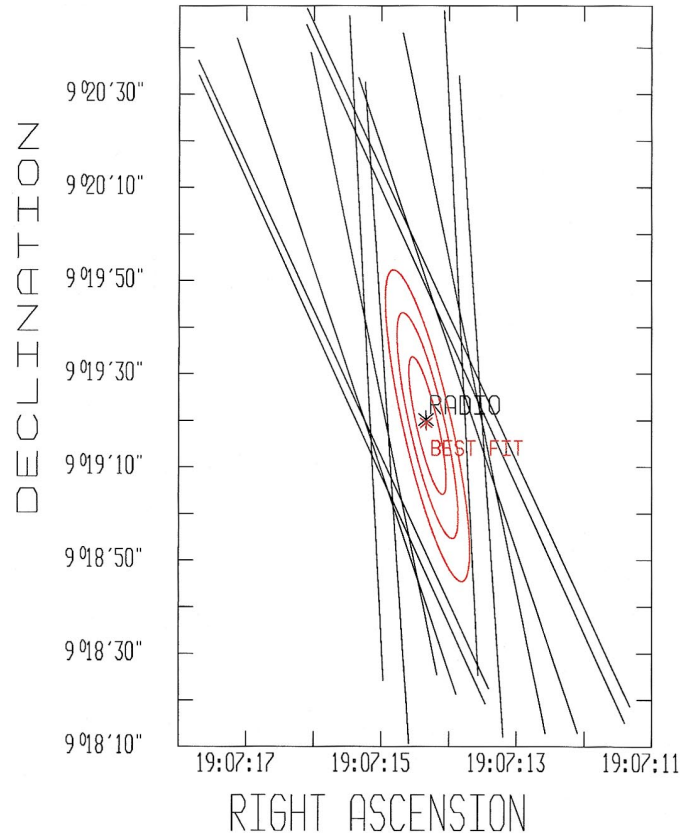

FIG. 1.—Six IPN annuli (*black lines*) and the 1, 2, and 3 σ equivalent confidence contours (*red annuli*) for SGR 1900+14. The best-fit position and the position of the radio source are also indicated.

excellent agreement between the VLA and triangulated positions of SGR 1900+14. The second is the agreement between IPN positions and the positions of gamma-ray bursts (GRBs) with optical counterparts (e.g., Hurley et al. 1997). The third and most stringent, however, is the confirmation of the *Ulysses* spacecraft timing and ephemeris by end-to-end timing tests, in which commands are sent to the GRB experiment at precisely known times and the times of their execution on board the spacecraft are recorded and compared with the expected times. Because of command buffering on the spacecraft, there are random delays in the execution of these commands, and the timing is verified to different accuracies during different tests. However, the tests before, during, and after the eight bursts in Table 1 took place on 1996 October 1, 1997 February 19, 1997 August 25, 1998 February 18, 1998 August 21, and 1999 March 7 and indicated that the timing errors at those times could not exceed 19, 21, 39, 29, 112, and 1 ms, respectively. For com-

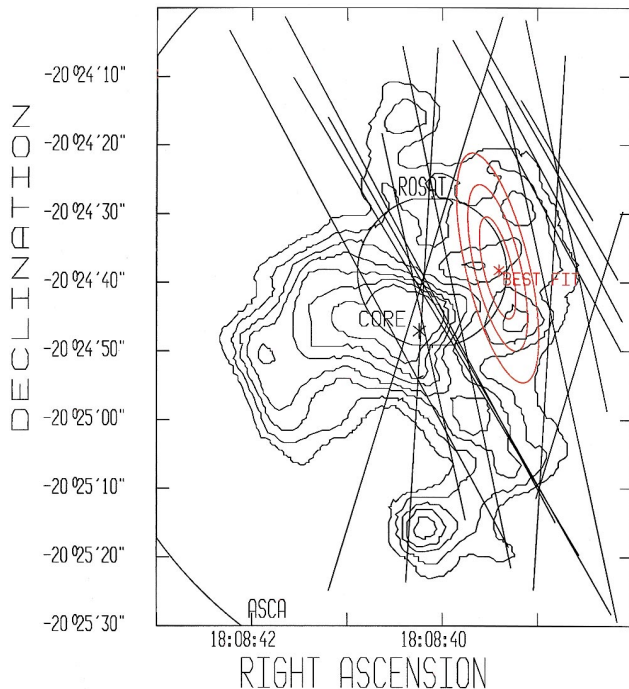| | | ANNULUS CENTER | | | 3 σ |
DATE	UT (s)	α(2000) (deg)	δ(2000) (deg)	RADIUS, θ (deg)	HALF-WIDTH (deg)
1998 May 26	80649	329.5855	−11.4558	47.3345	0.0037
1998 May 30	84457	329.6579	−11.2371	47.3091	0.0036
1998 Jul 19	30383	333.3281	−07.7778	49.3927	0.0031
1998 Sep 01	58382	339.0121	−03.7061	53.6270	0.0029
1998 Oct 22	56447	345.2596	+01.5599	58.6313	0.0029
1998 Oct 28	83020	345.8533	+02.2211	59.1029	0.0029

Fig. 2.—Eight IPN annuli (*black lines*) and the 1, 2, and 3 σ equivalent confidence contours (*red annuli*) for SGR 1806−20. The best-fit position and the position of the nonthermal core are indicated. The *ASCA* error circle is just visible in the lower left-hand and upper left-hand corners; its radius is 1′, quoted as a systematic error, with no confidence limit given (Murakami et al. 1994). The *ROSAT* PSPC error circle is at the center; its radius is 11″, with no confidence limit quoted (Cooke et al. 1993). We have reanalyzed the *ROSAT* data and confirm the presence of a weak source at this position, but we are unable to establish confidence limits for its position. The 3.6 cm radio contours of G10.0-0.3 are also shown, from Vasisht, Frail, & Kulkarni (1995).

parison, the 3 σ uncertainties in these triangulations have been taken to be 125 ms. This includes both the statistical errors, and a conservative estimate of unknown timing and spacecraft ephemeris errors. The low χ^2 values for the two SGR positions are probably due in part to this estimate. Thus, the most likely explanation of our results is indeed that SGR 1806−20 is not in the nonthermal core of G10.0-0.3, as has been assumed up to now. In this respect, SGR 1806−20 resembles SGR 1627−41, which also displays a significant displacement from the core of its radio SNR (Hurley et al. 1999b).

4. DISCUSSION

The association of the possible LBV of van Kerkwijk et al. (1995) with the SNR is compelling; they estimate that there are only several hundred stars this luminous in the Galaxy, and this one lies within 1″ of the radio peak. Indeed, in assuming a distance to the object of 6 kpc, they may have underestimated the star's luminosity; a better distance estimate is now

14.5 kpc (Corbel et al. 1997), giving a luminosity of 6 × 10^6 $L_\odot$. The fact that this object has not yet been observed to vary is not an argument against the LBV identification: Humphreys & Davidson (1994) note that LBVs do not *always* appear blue or variable. They are simply very luminous, unstable, hot supergiants that undergo irregular eruptions. In a giant eruption, they may radiate as much luminous energy as a supernova and eject a solar mass of material. But this does not explain the SGR bursts, the changing radio morphology, or the displacement between the radio core and the source of the bursts.

We propose that the LBV drives the morphological changes. LBVs are characterized by sporadic mass-loss rates of up to $\sim 10^{-4}$ $M_\odot$ yr^{-1} (Humphreys & Davidson 1994) and more. Moreover, these flows may be bipolar or jetlike, as in the case of η Car or P Cygni (Meaburn, Lopez, & O'Connor 1999). The measurements of van Kerkwijk et al. (1995) of the possible LBV in G10.0-0.3 indicate an outflow velocity of 500 km s^{-1}. Coupled with a mass-loss rate of 10^{-4} $M_\odot$ yr^{-1}, this gives a total wind energy of 2.5 × 10^{44} ergs yr^{-1}, or a factor of ∼30 greater than the rate of energy deposition into the radio nebula by the neutron star in the model of Frail et al. (1997). Thus, the LBV is easily capable of supplying the energy to explain the changing radio morphology. In the case of η Car, the LBV not only changes the morphology of its radio nebula dramatically but it also powers the (apparently nonthermal) radio nebula (Duncan et al. 1995; Duncan, White, & Lim 1997).

We believe that the magnetar model is the best current explanation for the bursts. It is possible that the SGR is not associated with the radio nebula and that we are simply observing a chance alignment of the two. But if the two are indeed associated, the SGR and the LBV may once have formed a binary system, which became unbound following the supernova explosion. In the magnetar model, the neutron star may be born with a kick velocity greater than 1000 km s^{-1} (Duncan & Thomson 1992). If we assume that the distance to SGR 1806−20 is 14.5 kpc (Corbel et al. 1997), that its age is 10,000 yr, and that the neutron star originated at the position of the LBV/nonthermal core, its approximate transverse velocity is a rather modest 100 km s^{-1}. (This estimate is subject to large uncertainties because of the unknown age of the SNR; also, the actual space velocity could be much larger.) This certainly does not strain the magnetar model, but it does raise another interesting question. Why did the SGR progenitor form a neutron star rather than a black hole, given that it must have been very massive to end its life earlier than the LBV? In any case, SGR 1806 now appears to be similar to the other SGRs in that there is no associated radio emission at its position, except for the brief radio flare from SGR 1900+14 (Frail et al. 1999).

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