A STELLAR WIND BUBBLE COINCIDENT WITH THE ANOMALOUS X-RAY PULSAR 1E 1048.1–5937: ARE MAGNETARS FORMED FROM MASSIVE PROGENITORS?

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ABSTRACT

We present 21-cm H I observations from the Southern Galactic Plane Survey of the field around the anomalous X-ray pulsar 1E 1048.1–5937, a source whose X-ray properties imply that it is a highly magnetized neutron star (a “magnetar”). These data reveal an expanding hydrogen shell, GSH 288.3–0.5–28, centered on 1E 1048.1–5937, with a diameter of 35 × 23 pc (for a distance of 2.7 kpc) and an expansion velocity of ≈7.5 km s⁻¹. We interpret GSH 288.3–0.5–28 as a wind bubble blown by a 30–40 M⊙ star, but no such central star can be readily identified. We suggest that GSH 288.3–0.5–28 is the wind bubble blown by the massive progenitor of 1E 1048.1–5937, and consequently propose that magnetars originate from more massive progenitors than do radio pulsars. This may be evidence that the initial spin period of a neutron star is correlated with the mass of its progenitor, and implies that the magnetar birth rate is only a small fraction of that for radio pulsars.

Subject headings: ISM: bubbles — ISM: individual (GSH 288.3–0.5–28) — pulsars: individual (1E 1048.1–5937) — radio lines: ISM — stars: winds, outflows — stars: neutron

1. INTRODUCTION

The last decade has revealed remarkable diversity in the young neutron star population: radio pulsars, soft γ-ray repeaters (SGRSs), anomalous X-ray pulsars (AXPs) and central compact objects (CCOs) are all now known to be potential compact remnants of core-collapse supernovae (e.g., Kaspi & Helfand 2002). While the CCOs remain enigmatic, the AXPs and SGRs are now both believed to be populations of “magnetars”, neutron stars whose persistent X-ray emission and occasional X- and γ-ray bursts are powered by the energy associated with extreme surface magnetic fields, ≥10¹⁵ G (see Woods & Thompson 2005, for a review).

The low Galactic latitudes and the associations of some of these sources with supernova remnants (SNRs) make it clear that magnetars are young neutron stars (Gaensler et al. 2001). However, what is not clear is why some neutron stars are “normal” radio pulsars, while others are X- and γ-ray emitting magnetars. The physical distinction cannot simply be the strength of the dipole magnetic field, since there is the order of 6 km s⁻¹, contributing to an error in the distance estimation (e.g., Zhang & Harding 2000; Kulkarni et al. 2003), as shown in Figure 1. The shell has a central velocity of ≈20, as shown in Figure 1. The shell has a central velocity of ≈20 km s⁻¹, which is a striking feature in the LSR V = –28 km s⁻¹; we thus designate this object GSH 288.3–0.5–28. At this central velocity, the major and minor axes of GSH 288.3–0.5–28 are 45' and 29', respectively. The images of l versus V and V versus V, also shown in Figure 1, demonstrate that GSH 288.3–0.5–28 is expanding, at a velocity V exp ≈7.5 km s⁻¹. GSH 288.3–0.5–28 is seen in multiple velocity planes, shows a high contrast between its walls and interior, and changes in angular extent as a function of velocity. It thus meets all the standard criteria for H I shells in the ISM (see McClure-Griffiths et al. 2002).

Standard rotation curves (e.g., Brand & Blitz 1993) forbid systemic motions having the central velocity observed for GSH 288.3–0.5–28, indicating significant deviations from circular rotation in this region. However, the shell’s central velocity matches the observed terminal velocity in this direction, which allows us to estimate a distance of 2.7 kpc from geometry alone. We assume that random cloud motions on the order of 6 km s⁻¹ contribute to an error in the distance es-
imate on the order of 40%, or 1 kpc. Incorporating both this distance uncertainty and the non-circular shape of the shell, we adopt a radius $R = 14 \pm 7$ pc. By integrating along a number of lines of sight through the shell walls and then subtracting a mean background, we find an average hydrogen column density through the shell walls of $(2.5 \pm 0.6) \times 10^{20} \text{ cm}^{-2}$. If this material uniformly filled the region into which the shell has expanded, the implied ambient number density is $n_0 = 17 \pm 9 \text{ cm}^{-3}$.

3. INTERPRETATION

3.1. The Nature of GSH 288.3–0.5–28

Shells like GSH 288.3–0.5–28 are common, and result from the effect of massive stars on the ISM. Specifically, GSH 288.3–0.5–28 could be an H II region, a SNR, or a stellar wind bubble. Below we brieﬂy consider these possibilities

The photoionizing ﬂux needed to maintain an H II region is $N_e \approx 4\pi R^2 n_0^2/3$, where $n_0 \approx 3 \times 10^{-11} \text{ cm}^{-3}$ is the recombination coefﬁcient for hydrogen (Osterbrock 1989). For the observed values of $R$ and $n_0$, we require $N_e \approx (3 \pm 2) \times 10^{50} \text{ s}^{-1}$. This is consistent with the ionizing ﬂuxes of the earliest-type stars, but such a source would also have a radio ﬂux of $> 100$ Jy at decimeter wavelengths. A radio continuum image of this region shows no such emission associated with GSH 288.3–0.5–28 (Green et al. 1999).

For the observed values of $n_0$, $R$, and $V_{exp}$, a SNR in the Sedov or radiative phases requires an initial explosion energy of $\approx 5 \times 10^{49}$ or $\approx 10^{50}$ ergs, respectively. These estimates are both well below the typical supernova explosion energy of $10^{51}$ ergs, making this interpretation unlikely. There is also no evidence in deep archival observations for any radio or X-ray SNR associated with 1E 1048.1–5937 (see Gaensler et al. 2001).

The remaining possibility is that GSH 288.3–0.5–28 is a wind-driven bubble. Using the wind bubble solution of Weaver et al. (1977), during the energy-conserving phase of expansion we expect that $R = 0.76(L/w_0)/t_0^{1/5}R_0^{1/5}$, where $t_0$ is the age of the bubble, $L_w$ is the wind luminosity of the central star, and $w_0$ is the density of the ambient medium. Since $V_{exp} = dR/dt$, we ﬁnd $L_w \approx (4 \pm 2) \times 10^{49}$ ergs s$^{-1}$ and $t_0 = 1.1 \pm 0.5$ Myr. The luminosity of the wind is a strong function of mass, allowing a reasonable typing of the associated central object (assuming only one star powers this bubble). In this case, an appropriate central source is an O6V star, with a mass-loss rate $\dot{M} \approx 2 \times 10^{-7} \text{ M}_\odot \text{ yr}^{-1}$ (de Jager et al. 1988), a wind velocity $\approx 2500 \text{ km s}^{-1}$ (Prinja et al. 1990), and a zero-age main sequence (ZAMS) mass of 30–40 $\text{ M}_\odot$ (e.g., Massey et al. 2002; Ostrov & Lapasse 2003).

3.2. GSH 288.3–0.5–28 and Carina OB1

We have shown that GSH 288.3–0.5–28 is most likely powered by the wind of a massive star at a distance of $2.7 \pm 1$ kpc. But can we identify the central star responsible for this bubble? There are many massive stars in this direction and at this distance, most of which are part of the association Carina OB1 at a distance of $\approx 2.5$ kpc (e.g., Humphreys 1978). However, we now argue that GSH 288.3–0.5–28 is unassociated with, and probably more distant than, the stars in Car OB1.

First, the collective winds of the massive stars in Car OB1 correspond to a total luminosity of $\approx 8 \times 10^{37}$ erg s$^{-1}$ (Abbott 1982). Combined with the powerful winds from stars in the nearby clusters Tr 14 and Tr 16, this should power a much larger expanding superbubble. Indeed such a larger shell, 100–200 pc across, has been identiﬁed in ionized, neutral and molecular gas (Cowie et al. 1981; Rizzo & Arnal 1998). Any individual star in this vicinity will not sweep up a neutral shell of its own but will contribute to the overall ionized supershell. Since the properties of GSH 288.3–0.5–28 are consistent with a single star sweeping up neutral gas, it seems unlikely that this shell is in the vicinity of Car OB1.

Second, the visual extinction toward the stars in Car OB1 is low, $A_V \lesssim 3$ (Humphreys 1978; Hoekzema et al. 1992). At this extinction and distance, a massive star should be clearly detected at the center of GSH 288.3–0.5–28. For example, the O6V star considered above would have a magnitude $V \gtrsim 9$. We have performed an exhaustive search for such sources (e.g., Humphreys 1978; Forte & Orosi 1981; Reed 1998; Kaltcheva 2003), from which the only catalogued massive star projected near the center of GSH 288.3–0.5–28 is IX Car (HD 94096; see Fig. 1), an M2Iab star with a mass of $\approx 20 \text{ M}_\odot$. The distance estimated to IX Car of $\sim 1.6$ kpc and its LSR radial velocity of $-17 \text{ km s}^{-1}$ (Humphreys 1978) suggests that it is a foreground object. Other massive stars in the vicinity, such as HD 93843, HD 94230, HD 305599 and LS 1976, all lie on the very edge or outside of GSH 288.3–0.5–28 in projection.

Finally, the photoionization from stars in Car OB1, most notably the OSIII star HD 93843, should fully ionize the shell. If we assume that the shell thickness is 20% of its radius, the edges of the shell should show Hα emission at a surface brightness of thousands of rayleighs. We have examined sensitive images of this region (e.g., Buxton et al. 1998; Gaustad et al. 2001); these show no Hα emission associated with GSH 288.3–0.5–28 down to much lower surface brightness limits. We therefore believe that GSH 288.3–0.5–28 is not exposed to the high ionizing ﬂuxes associated with Car OB1, but likely has a higher extinction than and is behind these coincident stars.

An important point is that the high extinction that we have invoked only need imply a slightly larger distance for the H I shell than for Car OB1, since extinction in this direction has little correspondence with distance. This is clear from consideration of the $\approx 30$ Wolf-Rayet (WR) stars within $3'$ of GSH 288.3–0.5–28 (van der Hucht 2001). For stars from this sample with distances in the range $1.7–3.7$ kpc as appropriate for GSH 288.3–0.5–28, $A_V$ can be as high as 6–7.

3.3. The Central Source Associated with GSH 288.3–0.5–28

If GSH 288.3–0.5–28 is not associated with any of the known bright stars in this direction, what is powering it? If the extinction to GSH 288.3–0.5–28 is signiﬁcantly higher than to the stars in Car OB1, its associated star might not be obvious. We ﬁrst consider K or M supergiants, which should be prominent in the near-infrared — we estimate a 1.3–$\mu$m magnitude $J \lesssim 0.5$ for a red supergiant at the distance to GSH 288.3–0.5–28. However, using the 2MASS point source catalog (Cutri et al. 2003), we ﬁnd no candidates for such a source inside GSH 288.3–0.5–28, other than IX Car (see §3.2). We searched for faint OB stars by considering the Tycho-2 catalog (Hog et al. 2000), which is 90% complete down to a V magnitude of 11.5. We assume that any massive star with $A_V \lesssim 4$ in this well-studied region would have been classiﬁed in earlier efforts, and so only consider stars with $A_V \gtrsim 4$. For standard reddening, this implies a color excess $E_{B-V} \gtrsim 1.3$ and hence for OB stars $B-V \gtrsim 1$. Just nine such stars from the Tycho-2 catalog lie within the perimeter of GSH 288.3–0.5–28, of which three are K or M stars with low extinction,
four have high proper motions which indicate that they are foreground objects, one is a foreground B1V star (LS 1956) which is heavily reddened, and one has near infrared magnitudes from 2MASS which are inconsistent with it being a massive star at the distance to GSH 288.3–0.5–28.

It is certainly possible that stars too faint to be in the Tycho-2 catalog could also be candidates. While we thus accept that we cannot make a definitive identification using available data, there is one remaining source, namely the AXP 1E 1048.1–5937, which we argue below represents a viable association with GSH 288.3–0.5–28. If 1E 1048.1–5937 generates a wind powered by its spin-down, as do many radio pulsars, then its spin parameters imply only $L_v \approx 4 \times 10^{32}$ erg s$^{-1}$ (Gavriil & Kaspi 2004). This is far too low to be responsible for the surrounding shell. However, an intriguing alternative is that GSH 288.3–0.5–28 was blown by the star whose collapse formed 1E 1048.1–5937. As for associations between pulsars and SNRs, the likelihood of this association should be judged by geometric correspondence, agreement in distance and age, and evidence for physical interaction.

First considering geometry, it is clear from Figure 1 that 1E 1048.1–5937 is close to the center of GSH 288.3–0.5–28 in projection. Isolated neutron stars generally have high space velocities, $\gtrsim 300$ km s$^{-1}$ (Arzoumanian et al. 2002), so that any neutron star older than $\sim 100$ kyr will have moved far from its progenitor’s wind bubble. Thus the association is only viable if we can argue independently that 1E 1048.1–5937 is extremely young. Indeed there is good evidence that this is the case, since associations with SNRs for other AXPs argue that these sources all have ages $\lesssim 10$ kyr (Gaensler et al. 1999, 2001). In this case the AXP should be centrally located in any progenitor wind bubble, as observed. We note that the “characteristic age” of 1E 1048.1–5937 is much higher than that for the Carina complex (which includes Car OB1) at a distance of $\approx 2.5$ kpc. It has thus been argued that 2.5 kpc is a firm lower limit on the distance to this source (Ozel et al. 2001). However, the high column to 1E 1048.1–5937 is still compatible with the distance to GSH 288.3–0.5–28. For standard gas to dust ratios, $N_H \approx 1.1 \times 10^{22}$ cm$^{-2}$ (e.g., Teng & Wolfire 2002), is much higher than that for the Carina complex (which includes Car OB1) at a distance of $\approx 2.5$ kpc. It has thus been argued that 2.5 kpc is a firm lower limit on the distance to this source (Ozel et al. 2001). However, the high column to 1E 1048.1–5937 is still compatible with the distance to GSH 288.3–0.5–28. For standard gas to dust ratios, $N_H \approx 1.1 \times 10^{22}$ cm$^{-2}$ implies a visual extinction $A_V \approx 5.8$ (Wang & Chakrabarty 2002). The WR catalogue of van der Hucht (2001) demonstrates that the level of extinction is consistent with distances in the range $\approx 2–12$ kpc in this region, so is easily reconciled with the distance to GSH 288.3–0.5–28.

Third, we need to determine if the age of GSH 288.3–0.5–28 is consistent with that expected for the progenitor of 1E 1048.1–5937. A star with a ZAMS mass of $\approx 30–40$ M$_{\odot}$ and solar metallicity lives for $\approx 5–6$ Myr (e.g., Meynet et al. 1994). Since the age of the AXP is negligible in comparison, this should also be the age of the surrounding bubble. However, in §3.1 we estimated an age for the shell of 1.1 ± 0.5 Myr. There is clearly a large discrepancy between these two estimates. However, this same age problem has been observed for many other H I shells around individual massive stars (e.g., Gervais & St-Louis 1999; Cappa & Herbstrmeyer 2000). There is no simple resolution to this discrepancy, although in some cases it may be explained by a “blow out” into a lower density environment (Oey & Smedley 1998). We conclude that any discrepancy between the ages estimated for GSH 288.3–0.5–28 and for the progenitor of 1E 1048.1–5937 is not a strong argument against their association.

Finally, we consider direct physical evidence that 1E 1048.1–5937 and GSH 288.3–0.5–28 are associated. Young neutron stars should be embedded in young SNRs, but for 1E 1048.1–5937 no such SNR is observed (Gaensler et al. 2001). A simple explanation is that the associated SNR is expanding into a low density bubble, so that it does not yet produce observable emission (e.g., Ciotti & D’Ercol 1989). Thus from the absence of a SNR, it is reasonable to expect that 1E 1048.1–5937 should show evidence for a surrounding cavity: GSH 288.3–0.5–28 clearly fulfills this prediction. For a SN shock velocity of 5000 km s$^{-1}$, the blast wave should impact the shell walls $\approx 3$ kyr after core collapse. The lack of any radio or X-ray emission from this event requires the neutron star to be younger than this, consistent with the small ages expected for AXPs.

To summarize, a very young neutron star with a massive progenitor should be centrally located in an expanding H I shell, with no evidence for a surrounding SNR. This is exactly what we observe for GSH 288.3–0.5–28 and 1E 1048.1–5937. Both sources are consistent with being at a distance of $\approx 3$ kpc, behind $\approx 6$ magnitudes of optical extinction.

### 4. IMPLICATIONS FOR MAGNETARS

As explained in §1 a fundamentally unresolved issue in the study of compact objects is why some neutron stars are ordinary radio pulsars, while others are magnetars. Since the initial mass function (IMF) sharply declines with increasing ZAMS mass, most neutron star progenitors will have masses near the minimum mass for core collapse, i.e., 8–9 M$_{\odot}$. We have presented evidence here that the progenitor of AXP 1E 1048.1–5937 was considerably more massive than this. For some SGRs, possible associations with massive star clusters similarly argue for high-mass progenitors (e.g., Klose et al. 2004; Eikenberry et al. 2004). We thus propose that the difference between normal pulsars and magnetars is the progenitor mass. We note that massive ($\gtrsim 25$ M$_{\odot}$) stars do not always form black holes: for solar metallicity, mass loss causes single stars heavier than $\sim 60$ M$_{\odot}$ to form neutron stars (Heger et al. 2003); a progenitor of lower mass (25–40 M$_{\odot}$) whose binary companion strips its outer envelope before core collapse can also form a neutron star (Fryer & Kalogera 2001).

Why should massive stars form magnetars? Duncan & Thompson (1992) and Thompson & Duncan (1993) argue that magnetars result from rapidly rotating ($P \sim 1$ ms) proto-neutron stars, in which an efficient large-scale dynamo operates in the first few seconds after birth, generating a super-strong magnetic field with significant multipolar components. Heger et al. 2005 have recently carried out a series of calculations of differentially rotating magnetized supernova progenitors. They find that magnetic torques are especially effective at transferring angular mo-
momentum away from the stellar core during the red supergiant and helium burning phases of evolution. For progenitors with masses \(\sim 10 - 15 \, M_\odot\), this results in neutron stars with initial periods \(\sim 10 - 15\) ms, too slow to generate magnetar-like fields. However for more massive stars, the reduced time interval between hydrogen depletion and the supernova results in limited braking of the core, producing much more rapidly spinning neutron stars. For example, a 35 \(M_\odot\) progenitor results in a neutron star of initial period 3 ms, in the range needed to give birth to a magnetar.

Within this scenario, we can immediately make a prediction as to the relative birth rates of radio pulsars versus magnetars. For argument’s sake, we suppose that the mass cut between normal pulsars and magnetars is at a ZAMS mass of 25 \(M_\odot\). Then for an IMF of slope \(\alpha = 2.35\) for massive stars \((dN/dM \propto M^{-\alpha}; [\text{Massey} 2003])\), only \(\sim 20\%\) of progenitors can potentially form magnetars. Since \(\sim 50\%\) of progenitors heavier than 25 \(M_\odot\) will form black holes [Heger et al. 2003], we infer that the magnetar birth rate is \(\sim 10\%\) of that of radio pulsars.

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Fig. 1.— $\text{H}_1$ in the field of the AXP 1E 1048.1–5937, from SGPS data. The three panels plot the surface brightness of $\text{H}_1$ as a function of Galactic longitude, Galactic latitude and LSR velocity. Each greyscale ranges between $-10$ and $+78$ Jy beam$^{-1}$, as shown by the scale bar on the upper right. The spatial resolution of the data are $142'' \times 125''$, while the velocity resolution is $0.82$ km s$^{-1}$. The upper right panel shows the image plane at an LSR velocity of $-28$ km s$^{-1}$; the positions of 1E 1048.1–5937 and of the star IX Car are marked by a cross and a star, respectively. The left panel shows a $b - \nu$ diagram at $l = 288^\circ 25$; the lower panel shows a $l - \nu$ diagram at $b = -0^\circ 52$. 