A “MISSING” SUPERNOVA REMNANT REVEALED BY THE 21 cm LINE OF ATOMIC HYDROGEN

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ABSTRACT

Although some 20,000–30,000 supernova remnants (SNRs) are expected to exist in the Milky Way, only about 230 are currently known. This implies that most SNRs are “missing.” Recently, we proposed that small (≤1°), faint, high-velocity features seen in large-scale 21 cm line surveys of atomic hydrogen (H i) in the Galactic plane could be examples of such missing old SNRs. Here we report on high-resolution H i observations of one such candidate, FVW 190.2+1.1, which is revealed to be a rapidly expanding (~80 km s$^{-1}$) shell. The parameters of this shell seem only consistent with FVW 190.2+1.1 being the remnant of a SN explosion that occurred in the outermost fringes of the Galaxy some ~3 × 10$^3$ yr ago. This shell is not seen in any other wave band, suggesting that it represents the oldest type of SNR, that which is essentially invisible except via its H i line emission. FVW 190.2+1.1 is one of a hundred “forbidden-velocity wings” (FVWs) recently identified in the Galactic plane, and our discovery suggests that many of these are likely to be among the oldest SNRs. We discuss the possible link between FVWs and fast-moving atomic clouds in the Galaxy.

Subject headings: radio lines: ISM — supernova remnants

1. INTRODUCTION

From radio and X-ray studies of the Milky Way, about 230 supernova remnants (SNRs) are known (Green 2004$^1$). However, a supernova (SN) outburst occurs every 30–50 yr on average in a galaxy like the Milky Way (van den Bergh & McClure 1994; Cappellaro et al. 1999). Hence, if ~10$^8$ yr is taken to be the lifetime of a SN, the total number of remnants in our Galaxy should be (2–3) × 10$^4$. This suggests that most SNRs are “missing.”

Recently, we proposed that small (≤1°), faint, high-velocity features seen in large-scale 21 cm line surveys of atomic hydrogen (H i) in the Galactic plane could be examples of such missing old SNRs (Koo & Kang 2004; Kang 2004). These “forbidden-velocity wings” (FVWs) appear in longitude-velocity diagrams as low-level, yet significant, bumps protruding from the regular Galactic H i emission (Fig. 1). The smooth boundary of the H i distribution in Figure 1 is given by the extent and rotational properties of the Galactic gaseous disk. Small-scale features lying significantly beyond these boundaries are likely to have originated from energetic phenomena. The strong, discrete emission feature at v$_{LSR}$ = 196 km s$^{-1}$ at l = 190° is a typical example.

We noted that there are many such FVWs of unknown origin in the Galactic plane and that these look similar to H i features observed toward old SNRs. In the late stages of their evolution, SNRs are expected to develop dense atomic shells that emit in the H i 21 cm line. However, because of confusion with emission from atomic gas along the line of sight, the H i radiation from a SNR shell is only observable when its expansion velocity extends significantly beyond the maximum and/or minimum velocities permitted by Galactic rotation, i.e., when its H i emission appears as a protrusion in velocity (see Fig. 1). Systematic studies have been previously made toward 200 known SNRs, but high-velocity H i wings have only been detected toward two dozen (Koo & Heiles 1991; Koo et al. 2004). It was pointed out that this relatively low detection rate is because these studies focused exclusively on cataloged radio-continuum/X-ray–emitting SNRs, hence excluding old SNRs that have become too faint to be recognized in these ways (Koo & Kang 2004). Recent sensitive, high-resolution, radio continuum and X-ray observations have discovered several very faint SNRs, indicating that there are indeed many old SNRs awaiting discovery (Brogan et al. 2004; Schaudel et al. 2002). However, while we have proposed that the FVWs are candidates for such missing old SNRs, existing Galactic plane H i surveys have insufficient resolution and/or sensitivity to reveal their true natures (Hartmann & Burton 1997; McClure-Griffiths et al. 2005; Taylor et al. 2003).

In this Letter, we present the results of high-resolution H i observations of FVW 190.2+1.1, the FVW shown in Figure 1, which show it to be a rapidly expanding shell, probably originating from a SN explosion.

2. OBSERVATIONS

In 2004 and 2005 February, we used the Arecibo 305 m telescope$^2$ to obtain a high-resolution (HPBW = 3.4") H i image of FVW 190.2+1.1. Total-intensity 21 cm spectra with a total bandwidth of 3.125 MHz and 1024 frequency channels were obtained using the dual-channel, linear polarization, L-wide receiver. This gave a velocity coverage of 660 km s$^{-1}$ and a velocity resolution of 1.29 km s$^{-1}$ after Hanning smoothing. A rectangular area of 20′ × 16′ centered at (α$_{2000.0}$, δ$_{2000.0}$) = (6°12′00′′, 20°32′00′′) was mapped using fixed-azimuth drift scanning, with

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$^1$ Also available at http://www.mrao.cam.ac.uk/surveys/snrs.

$^2$ The Arecibo Observatory is part of the National Astronomy and Ionosphere Center, which is operated by Cornell University under a cooperative agreement with the National Science Foundation.
a 1.7 step in declination. The resulting spectra were converted into antenna temperature and then gridded via convolution to produce a data cube with a pixel size of 1.7' and a final half-power beamwidth (HPBW) of 3.9'. A polynomial baseline of order 2–5 was subtracted from each spectrum. The rms (1 σ) noise in the cube is ~0.05 K.

In addition, in 2005 January we searched for 2.5 GHz synchrotron emission from the shell of FVW 190.2+1.1 using the Green Bank Telescope (GBT). Both linear polarizations were recorded using the dual polarization S-band receiver centered at 2.53 GHz and the GBT digital continuum receiver with a bandwidth of 12.5 MHz. A rectangular area of 2.5' × 2.0' centered at (α2000.0, δ2000.0) = (6°13'00'', 20°40'00'') was mapped using “on-the-fly” data acquisition, with a scanning rate of 2' minute⁻¹ along right ascension and a 2.0' step in declination. The sampling interval was 0.1 s. Noise power was injected on alternate samples to permit calibration of the total signal (including emission from the atmosphere, ground, and Galactic background) into system temperature. We obtained data for just the “source component” by subtracting a smooth baseline from each scan. The resulting data were gridded by convolution to produce an image with a pixel size of 2.0' and a HPBW of 4.7'. We have compared the surface brightness across the intense, extended radio source Sh 2-252, situated within the field, to that from the Bonn 11 cm survey (Fürst et al. 1990). There was an excellent correlation between the two, although the brightness scale of the present data was lower than that of the Bonn image by 23% and 37% for our respective orthogonal polarizations. We have scaled our data to that from Bonn by multiplying each polarization by the appropriate constant value. The final image was produced by combining the brightness distributions for the two polarizations and smoothing this with a Gaussian beam of 1 pixel dispersion, giving a HPBW of 4.7'. The rms (1 σ) noise on the image is ~6 mK.

3. RESULTS

Figure 2 shows the Arecibo H I emission images of FVW 190.2+1.1 for different velocity intervals, together with a three-color map generated from these. An ~1''-sized, mildly elliptical, shell structure is clearly seen, with its major axis aligned roughly east-west. The emission ring becomes smaller the more positive the LSR velocity (Fig. 3), indicating that we are seeing that portion of a shell that is expanding away from us. While the shell structure is visible for velocities between about 25 and 84 km s⁻¹, the end cap is not seen. The end cap is expected to be faint because of the spreading of the H I intensity over a range of velocities due to turbulence within the shell (Koo & Heiles 1995; Cazzolato & Pineault 2005). However, the upper limit on the H I column density of the end cap of FVW 190.2+1.1 is very low, e.g., 1.6 × 10¹⁸ cm⁻² (3 σ) over velocities between 85 and 95 km s⁻¹, suggesting that the shell is probably incomplete toward this direction. The constant angular diameter at lower velocities indicates that this should be close to the size of the expanding shell and that its systemic velocity is vₑ ≲ 30 km s⁻¹. Another point to vₑ exists. To the east of the region studied, for vₑ ≤ 35–55 km s⁻¹, there is faint background emission whose intensity drops steeply across the eastern ridge of the shell (see the G and B images in Fig. 2), indicating that this external emission is from ambient gas interacting with the shell. We see only the wing portion of this emission, and, by least-squares fitting of the 21 cm line profile with several Gaussian components, we obtain a central velocity of ≥10 km s⁻¹ for this component. Therefore, we have 10 km s⁻¹ ≤ vₑ ≤ 30 km s⁻¹ and adopt vₑ = 20 ± 5 km s⁻¹, where the error is a probable error.
(Bevington 1969). In this direction, the LSR velocity is a shallow function of distance so that the systemic velocity does not yield a good kinematic distance. Nevertheless, the systemic velocity is reliable, even if the distance to FVW 190.2 + 1.1 is only poorly constrained.

Expansion parameters for FVW 190.2 + 1.1 can be derived from the velocity-size dependence shown in Figure 3. The simplest model is a spherical shell expanding radially with uniform velocity. For this, the dotted curve shows the best-fit model, which has an angular radius of \( \bar{a} = 0 \pm 0.63 \) and an expansion velocity of \( \bar{v}_{\text{exp}} = 77 \pm 6 \text{ km s}^{-1} \). In practice, the velocity-size relation derived appears to possess more of a linear form than the concave shape predicted by the model. This difference can be explained by turbulent motions within the shell; e.g., the H\( \beta \) emission lines are broadened by turbulent motions, and this broadening makes the relation appear more linear. For example, the solid curve in Figure 3 shows the result for a partially complete spherical shell with the above expansion velocity but a slightly (3\%) larger diameter and a line-of-sight turbulent velocity dispersion of 10 km s\(^{-1} \).

We therefore consider that the simplest model provides an acceptable description of the expansion properties of FVW 190.2 + 1.1 and adopt \( \bar{a} = 0 \pm 0.63 \pm 0.03 \) and an expansion velocity of \( \bar{v}_{\text{exp}} = 77 \pm 6 \text{ km s}^{-1} \). For convenience, we normalize the physical parameters to a distance of 10 kpc, giving a geometrical mean radius \( \bar{R} = 110 d_{10} \) pc, while the major and minor axes of the shell (42' × 34') correspond to (120 × 99)\( d_{10} \) pc, where \( d_{10} \) is the distance to FVW 190.2 + 1.1 in units of 10 kpc.

We derive the mass of the shell using the channel maps. In each map, we use nested elliptical rings to estimate how the mean H\( \beta \) intensity varies with distance from the geometrical center. The elliptical rings have an axial ratio of 1.24 (\( = 42'/34' \)) and a thickness of 1.7 (= pixel size) along the major axis. The plot of the mean H\( \beta \) intensity as a function of radial distance reveals a bump that peaks at the location of the shell. We fit a smooth baseline and obtain the integrated H\( \beta \) flux density in the bump that can be easily converted to mass given that the H\( \beta \) emission is optically thin. The derived H\( \beta \) shell mass over the velocity range of 40–80 km s\(^{-1} \) is \((1.4 \pm 0.3) \times 10^5 d_{10}^2 M_{\odot} \). The mass per unit velocity interval increases as the velocity decreases. This is a general trend for rapidly expanding shells and has been attributed to the clumpy nature of the interstellar medium (e.g., Giovanelli & Haynes 1979; Koo & Heiles 1991). In order to derive the total H\( \beta \) mass of the expanding shell, we need to estimate the mass in the unobserved portion of the shell lying at lower velocities (\( \lesssim 40 \text{ km s}^{-1} \)) where the background H\( \beta \) emission dominates. The mass distribution can be described by a Gaussian, and we estimate the total mass by fitting a Gaussian centered at \( v_0 \). The extrapolated total H\( \beta \) mass of the shell is \( 6.5 \times 10^5 d_{10} M_{\odot} \). Including the cosmic abundance of helium, the corresponding kinetic energy of the shell is \( E_k \approx 5.4 \times 10^{50} d_{10} \) ergs. The large extrapolation factor means that the estimated total mass has a greater relative uncertainty. However, if the energetic phenomenon that produced the expanding shell had spherical symmetry, the derived kinetic energy should be reasonably (\( \sim 30\% \)) accurate.

As seen from Figure 2 (lower right panel), no 2.5 GHz continuum emission is detected from FVW 190.2 + 1.1 with an (3\%) upper limit of 0.02 K, corresponding to a 1 GHz surface brightness of \( 7 \times 10^{-23} \) W m\(^{-2} \) Hz\(^{-1} \) sr\(^{-1} \), when we assume that flux density varies with frequency as \( \nu^{0.8} \), with \( \alpha = 0.5 \). The shell is seen in neither the Infrared Astronomical Satellite maps at 60 and 100 \( \mu \)m nor the distribution of their ratio. It is also not seen in Digitized Sky Survey optical, Virginia Tech Spectral-Line Survey H\( \alpha \), or ROSAT X-Ray All-Sky Survey images (Finkbeiner 2003).

### 4. DISCUSSION

FVW 190.2 + 1.1 has a large (\( \sim 80 \text{ km s}^{-1} \)) expansion velocity. Although there have been discoveries of expanding H\( \beta \) shells and supershells, their expansion velocities are usually \( \lesssim 20 \text{ km s}^{-1} \) (Stil & Irwin 2001; Uyaniker & Kothes 2002; Heiles 1979). H\( \beta \) shells with expansion velocities comparable to that of FVW 190.2 + 1.1 have only been found toward old SNRs (Giovanelli & Haynes 1979; Koo & Heiles 1991; Koo & Kang 2004 and references therein), suggesting a SN origin for this shell. For a SNR shell, the initial explosion energy, \( E_{\text{SN}} \), can be estimated from \( E_{\text{SN}} = 6.8 \times 10^{48} n_0^{-3/2} R_1^{-1} v_{\text{exp}}^{1/2} M_{\odot} \) ergs, where \( n_0 \) is the ambient density of hydrogen nuclei in cm\(^{-3} \), \( R_1 \) is in parsecs, \( v_{\text{exp}} \) is in kilometers per second, and \( M_{\odot} \) is the metallicity (Cioffi et al. 1988). We estimate the ambient density for FVW 190.2 + 1.1 by assuming that the current H\( \beta \) mass in the shell was initially distributed uniformly over the volume contained within the shell. This yields \( n_0 = 0.048 d_{10}^{-2} \) cm\(^{-3} \). The metallicity in the outer Galaxy is significantly lower than in the solar neighborhood, and we adopt \( M_0 = 0.2 \), which is the metallicity at \( d = 10 \) kpc based on Maciel & Quireza (1999). However, since the SN energy depends only very weakly on the metallicity, the following discussion will not be affected by our adopted metallicity. Substituting these values, \( E_{\text{SN}} = 1.5 \times 10^{51} d_{10} \) ergs. For the canonical value of \( E_{\text{SN}} = 1 \times 10^{51} \) ergs, this implies a distance of 8 kpc, corresponding to \( R_1 = 88 \) pc and a dynamical age of \( t = 0.3 R_1/\nu_0 = 3.4 \times 10^4 \) yr. The distance appears rather larger than expected for a SN explosion in the Galaxy but is not unreasonable. It is also consistent with the empirical surface brightness–diameter (\( \Sigma-D \)) relation for SNRs. Extrapolating the \( \Sigma-D \) relation of Case & Bhattacharya (1998), we note that our 1 GHz continuum brightness upper limit is comparable to that predicted for a SNR shell of radius \( R_1 \sim 100 \) pc. Despite the

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\(^3\) The ROSAT X-Ray All-Sky Survey is available at http://www.xray.mpe.mpg.de/cgi-bin/rosat/rosat-survey.
large scatter of the $\Sigma$-D relation, this is also consistent with FVW 190.2+1.1 being a large, old SNR. We further note that several Sharpless H II regions have been discovered at such distances toward the anticenter region, including Sh 2-259, which is at 8.3 kpc toward $(l, b) = (192^\circ, 0^\circ63^\circ)$ and has a similar radial velocity to FVW 190.2+1.1 (22.8 $\pm$ 0.5 km s$^{-1}$; Moffat et al. 1979; Brand & Blitz 1993). Moffat et al. (1979) proposed the existence of a remote spiral arm connecting these H II regions from $r = 150^\circ$ to $220^\circ$, and it is quite possible that FVW 190.2+1.1 is a SNR associated with this.

Large, fast-expanding shells can also be produced by stellar winds from OB stars. The wind luminosity required to drive such a shell, and no morphological connection is apparent between the H II region and the shell. Also, if the shell were to have been produced by an O6.5 star, it would not be expected to be neutral because of the strong ionizing radiation. We further note that many HVCs forming a complex chain have been observed near $\sim$200 km s$^{-1}$ in this region of the anticenter (Mirabel & Morras 1990). These HVCs are colliding with the Galactic gaseous disk and generating a huge ($\sim$30$^\circ$) H I supershell, essentially all of whose gas is moving at negative radial velocities (Tamanaha 1997). FVW 190.2+1.1 is much smaller and is seen at positive radial velocities, making it unlikely to be associated with the HVCs. Summarizing, the large scatter of the relation, this is also consistent with FVWs. The nature of FVWs and their relation to the Galactic structure should soon be revealed by new high-sensitivity, high-resolution H I surveys such as those recently undertaken with the Arecibo L-band Feed Array (ALFA).

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