A LARGE ATOMIC HYDROGEN SHELL IN THE OUTER GALAXY: SUPERNOVA REMNANT OR STELLAR WIND BUBBLE?

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ABSTRACT

We report the detection of a ringlike H i structure toward l = 90°0, b = 2°8, with a velocity of v_{LSR} = -99 km s^{-1}. This velocity implies a distance of d = 13 kpc, corresponding to a Galactocentric radius of R_{gal} = 15 kpc. The l-v_{LSR} diagram implies an expansion velocity of v_{exp} \approx 15 km s^{-1} for the shell. The structure has an oblate, irregular shell-like appearance, which surrounds weak infrared emission as seen in the 60 \mu m Infrared Astronomical Satellite data. At a distance of 13 kpc the size of the object is about 110 \times 220 pc and placed 500 pc above the Galactic plane, with a mass of 10^5 M_{\odot}. An expanding shell with such a high mass and diameter cannot be explained by a single supernova explosion or by a single stellar wind bubble. We interpret the structure as a relic of a distant stellar activity region powered by the joint action of strong stellar winds from early-type stars and supernova explosions.

Subject headings: H ii regions — ISM: atoms — ISM: bubbles — ISM: kinematics and dynamics — supernova remnants

1. INTRODUCTION

There is no generally accepted overall picture of the spiral arm structure in the Galaxy, although we do know that there are star-forming regions beyond the Perseus arm (Wooden 1971; Sabinin, Bianchini, & Strafella 1986). The H ii region region BG 2107+49, for instance, is known to be at R_{gal} = 14 kpc (Higgs et al. 1987) and Chromey (1979) found OB stars at Galactocentric radii of R_{gal} = 15–25 kpc. Furthermore, Chini & Wink (1984) and Blitz, Fich, & Stark (1992) reported H ii regions at R_{gal} \approx 18 kpc and Digel, de Geus, & Thaddeus (1994) found molecular clouds associated with H\alpha emission at R_{gal} = 18–28 kpc, whose kinetic temperature was comparable to that of local star-forming regions. One of the clouds they found, designated as Cloud 2, has a kinematic distance of R_{gal} \approx 28 kpc (de Geus et al. 1993; Digel et al. 1994). Recently, Kobayashi & Tokunaga (2000) have observed young stellar objects associated with Cloud 2 and suggested a smaller Galactocentric distance (~20 kpc). In addition, recent data show that Cloud 2 is associated with a larger H i ring (GSH 138–01–94; Stil & Irwin 2001). These authors interpret this object as snow-plowed material resulting from a single supernova (SN) event.

The optical disk of the Galaxy may extend as far as 20 kpc from the Galactic center. The atomic gas, on the other hand, extends to a much greater radius: R_{gal} \approx 30 kpc. Detection of star-forming and H ii regions beyond the optical disk provides information about the composition of the Galactic disk. The presence of these H ii regions could explain the ionization of the diffuse gas at these large distances and hence give the extent of the magneto-ionic medium in the Galaxy. At these distances the only possible objects that may be linked to the observed ionized gas are stars; because the general interstellar radiation field is weaker, metallicity is lower (Shaver et al. 1983; Fich & Silkey 1991) and there is less cosmic-ray flux (Bloemen et al. 1984).

H ii regions far from the galactic center are, in fact, a common phenomenon in spiral galaxies similar to the Milky Way. Ferguson et al. (1998) have detected H\alpha emission from star-forming regions in the extreme outer regions of the three nearby late-type spiral galaxies, NGC 628, NGC 1058, and NGC 6946. Lelievre & Roy (2000) identified 137 H ii regions beyond a radius of ~16 kpc, with narrow-band H\alpha imaging in the galaxy NGC 628. M31 also has stellar activity in its outer disk; Cuillandre et al. (2001) found a population of B stars correlated with the extended H i distribution of M31.

With increasing distance from the Sun, the spatial resolution of telescopes decreases. While single-antenna data can be used to probe the H i cloud concentrations (Digel et al. 1994), high-resolution data are required to resolve these structures. The new data at ~l' resolution provided by the Canadian Galactic Plane Survey (CGPS; Taylor et al. 2002) are well suited to study the structure and dynamics of H i regions at the edge of and even beyond the optical disk. Such a structure detected serendipitously south of the supernova remnant (SNR) HB 21 in the CGPS database is the topic of this paper. This paper makes an attempt to clarify the possible origin of such large H i structures far from the Galactic center. We analyze the H i spectral line data together with the available continuum data at 1420 MHz and infrared data to show that the detected structure is the result of the joint action of strong winds from early-type stars and SN explosions. We demonstrate that H i spectral line observations provide a very efficient method of tracing stellar activity at large distances from the Galactic center, but not many such structures have been detected because of the lack of data of sufficiently high resolution covering large areas.

2. H i OBSERVATIONS

The H i line observations were carried out with the Dominion Radio Astrophysical Observatory (DRAO)
synthesis telescope (Landecker et al. 2000) as part of the CGPS. A detailed description of the data processing routines can be found in Willis (1999). The low spatial frequency H i data are from the Low-Resolution DRAO Survey of the CGPS region observed with the DRAO 26 m telescope (Higgs & Tapping 2000). Parameters relevant for the H i data are given in Table 1.

3. THE H I RING

We have detected an H i shell at \((l, b) = (90^\circ, 2^\circ 8)\) in the H i survey data of the CGPS (see Figs. 1 and 2). A shell-like structure appears in the foreground Perseus arm gas at about \(v_{\text{LSR}} = -90\ km\ s^{-1}\). It slowly expands and gets more prominent with higher negative velocities. It is most pronounced at a velocity of \(v_{\text{LSR}} = -99\ km\ s^{-1}\). At further negative velocities it becomes smaller and fainter until it disappears at about \(v_{\text{LSR}} = -114\ km\ s^{-1}\). We call this structure GSH 90+03–99, in accordance with the current nomenclature for Galactic atomic shells.

The atomic hydrogen map integrated between \(v_{\text{LSR}} = -94\) and \(-106\ km\ s^{-1}\) is given in Figure 3. The structure is about \(0.5^\circ \times 1^\circ\) in size. The radial velocity of \(-99\ km\ s^{-1}\) corresponds to a kinematic distance of 13 kpc, which would give our H i structure a linear size of \(110 \times 220\ pc\) in \(l\) and \(b\), according to a flat Galactic rotation curve with \(R_0 = 8.5\ kpc\) and \(v_0 = 220\ km\ s^{-1}\). Towards the structure there is a very faint 1420 MHz continuum and infrared emission. In Figure 4 we display the longitude-velocity diagram of the structure. Behind the Perseus arm at the exact center of the detected H i structure, we see a shell-like feature moving toward us, while the receding part is buried in the Perseus arm gas at lower negative velocities. This structure extends up to \(v_{\text{LSR}} = -114\ km\ s^{-1}\). As a result, the deduced expansion velocity of the H i ring is \(v_{\text{exp}} \approx 15\ km\ s^{-1}\). The mass of the structure is about \(10^5\ M_\odot\) that together with the expansion velocity gives a kinetic energy of \(2.3 \times 10^{50}\ ergs\) currently in the expanding shell, comparable to the explosion energy of an SNR. However, at such a low expansion velocity the SNR should already be at the end of the radiative phase, with most of its energy radiated away, and therefore no longer “visible” in continuum emission.

The kinematic age of the observed shell \(t = \alpha R/v_{\text{exp}}\), with a mean radius \(R = 80\ pc\), would result in an age of \(1 \times 10^6\ yr\) for a radiative SNR (\(\alpha = \frac{1}{2}\)) and \(3 \times 10^6\ yr\) for a supershell (\(\alpha = \frac{3}{2}\)). For GSH 138–01–94, these values are \(4 \times 10^6\ yr\) and \(9 \times 10^6\ yr\), respectively. Apparently the object is too old to be an SNR, which typically has an observable life span of \(10^5\ yr\). This obtained age, on the other hand, is young in comparison with the distant Galactic shells listed by Heiles (1984), which are \(\sim 10^7\ yr\) old, have typical energies of \((1-5) \times 10^{52}\ ergs\), and are usually up to 10 times larger than the detected structure. Nevertheless, the object has a mass comparable to that of distant Galactic shells and yet a size comparable to that of local shells. For instance, the Local Bubble, North Polar Spur, and Gum Nebula are just twice as large as this H i shell (Heiles 1998).

We have checked the region in the Columbia CO survey (Dame et al. 1987). There is no evidence of associated molecular material. However this survey has coarse angular resolution and is undersampled. Especially the area of interest has a low signal-to-noise ratio; a signal below 0.5 K could not be detected. The maximum molecular hydrogen column density would be \(N_{\text{H}_2} \approx 1.2 \times 10^{20}\ cm^{-2}\ km^{-1}\ s^{-1}\). Assuming a molecular material distribution comparable to the atomic hydrogen distribution, a maximum molecular mass of \(M \approx 10^5\ M_\odot\), for instance, could stay undetected in the velocity interval shown in Figure 1. Thus, nondetection in the Columbia data does not necessarily mean that there is no molecular gas in the region.

3.1. Would It Be Possible to Identify Any Related Stars?

H II regions are expected to include stars. However, stellar light suffers from absorption and reddening by the intervening material. Therefore, beyond a certain distance stars of an H II region cannot be observed.

At the northwestern part of the structure there is the UV star L110 (Lanning & Meakes 1994), located at \(l = 89^\circ 9\) and \(b = 2^\circ 91\). We have calculated the H i absorption profile of a nearby extragalactic source at \((l, b) = (89^\circ 93, 3^\circ 05)\) and thereby found a foreground H i column density of \(9.6 \times 10^{21}\ cm^{-2}\). Combining that with the observed optical parameters of the star results in a color of \((U-B)_{0} = -1.85\). An O3 star would have \((U-B)_{0} = -1.22\). Therefore, this UV star must be located in front of the Perseus arm, rather than behind it. This star is apparently not related to the detected structure. This also demonstrates that the detection of stars within the structure would be difficult.

To clarify whether massive stars in the H i structure are observable, we have calculated extinction and reddening of typical O and early B-type stars, based on the foreground H i column density and the distance. The measured foreground H i column density is \(9.6 \times 10^{21}\ cm^{-2}\), which corresponds to a reddening of

\[
E_{B-V} = \frac{N_{\text{H}_2}}{4.8 \times 10^{21}\ cm^{-2}} = 2.0\ mag
\]

as given by Bohlin, Savage, & Drake (1978). This gives a visual extinction of \(A_V = 6.4\ mag\).

A typical, main-sequence O3 star has an absolute magnitude of \(M_V = -6.0\ mag\) and color indices of \((B-V)_0 = -0.33\) and \((U-B)_0 = -1.22\). The above reddening and extinction in turn correspond to apparent visual magnitudes of \(m_V = 16\ mag\), \(m_B = 17.7\ mag\), and \(m_{U-V} = 18\ mag\).

For a main-sequence B1 star, with \(M_V = -3.2\ mag\) and color indices of \((B-V)_0 = -0.27\) and \((U-B)_0 = -0.95\), the above calculation yields visual magnitudes of \(m_V = 18.8\ mag\), \(m_B = 20.5\ mag\), and \(m_{U-V} = 21.2\ mag\). We note that for both O3 and B1 stars the observed color indices are \((B-V) > 0\) and \((U-B) > 0\). Lanning & Meakes (1994) have detected stars in this region in the range from \((U-B) = 0\) to \(-1.5\) and in magnitude from \(m_{U-V} = 10–21\ mag\). Therefore, stars with positive \((U-B)\), such as those that were mentioned above, are missing from their list.
These calculations show that deep measurements have to be made in order to detect early-type stars that may contribute to the energy budget of the H i ring by their stellar winds. Near-infrared measurements, on the other hand, might provide further hints about the existence of embedded, young OB clusters inside the H i structure, like those found in GSH 138–01–94 (Kobayashi & Tokunaga 2000), since there exists an infrared source in the area enclosed by the H i shell (see § 4). However, such sensitive near-infrared data toward GSH 90+03–99 are currently not available.

4. OTHER OBJECTS IN THE REGION
The infrared source IRAS 20565+5003 is located almost at the center of the H i structure. According to Bronfman, Nyman, & May (1996) the flux ratios 25 \( \mu \text{m} / 12 \, \mu \text{m} (>3.7) \) and 60 \( \mu \text{m} / 12 \, \mu \text{m} (>19.3) \) indicate a compact H ii region. The observed infrared intensities for our source (0.91, 3.50, and 31.57 Jy, at 12, 25, and 60 \( \mu \text{m} \), respectively) make this source a strong candidate for an H ii region. Rudolph et al. (1996) observed 10 IRAS point sources at distances of \( R_{\text{gal}} \) 15–18 kpc, with the VLA at 2 and 6 cm. They found that the spectral indices of these sources are consistent with the optically thin free-free emission from H ii regions, signaling stellar activity at large distances. The distance of IRAS 20565+5003 is unknown, and we have only circumstantial evidence that it is located within the H i ring. Therefore, an association between the two is not certain, although the positional coincidence is attractive and compelling. Other IRAS sources in the region are away from the H i structure or do not satisfy the required infrared ratio criteria.
The H\textsuperscript{ ii} region BFS 4 at $(l, b) = 90^\circ.32, +2^\circ.67$ is also in the region. However, the observed radial velocity of BFS 4, $1.1 \pm 0.5$ km s$^{-1}$ (Blitz et al. 1982), implies that it is a local object.

5. SUPERNOVA REMNANT OR OB ASSOCIATION?

The observed H\textsuperscript{ i} structure may be attributed to an old SNR, which has already cooled to temperatures at which ionized hydrogen recombines and creates the observed H\textsuperscript{ i} shell. Assuming the structure is the result of such an event, we can calculate the maximum radius of the SNR as a function of the explosion energy and the ambient density. The mass of the observed H\textsuperscript{ i} structure is about $10^5 M_\odot$, comparable to a typical giant molecular cloud, assuming the gas is optically thin. Thus, we obtain $n_0 \simeq 2.0$ cm$^{-3}$ before the structure was formed. Due to the high Galactocentric radius of the H\textsuperscript{ i} ring, we have to take the metallicity into account, because lower metallicity causes slower cooling, which in turn results in a lower energy loss rate. Hence, in the outer Galaxy, SNRs live longer. There are two recent publications dealing with the dynamics of SNRs at late stages of their evolution and taking metallicity effects into account (Cioffi, McKee, & Bertschinger 1988; Thornton et al. 1998; the latter is based on the central equations of the former). Both discuss the so-called radiative expansion or snowplow phase at the end of SNR evolution. This phase consists of two parts: the cooling-dominated first part and, later, the merger with the interstellar medium. At the end of the first part the SNR is no longer distinguishable from the environment. Thus, we adopt the radius at the end of the first part as the maximum observable radius of an SNR. Following Cioffi et
HI $-94 \leq v_{\text{LSR}} \ (\text{km s}^{-1}) \leq -106$

Fig. 3.—H$\,\text{i}$ emission toward the detected ring of neutral hydrogen integrated between $-94$ and $-106 \text{ km s}^{-1}$

Fig. 4.—Longitude-velocity diagram of the detected H$\,\text{i}$ structure. The arrow marks the approaching shell.
TABLE 2
CHARACTERISTICS OF THE TWO H I RINGS CALCULATED FROM EQUATION 2

| Object            | $\zeta$ | $R_{\text{merge}}$ (pc) | $E_0$ ($\times 10^{51}$ ergs) | $d_{\text{max}}$ (kpc) |
|-------------------|---------|--------------------------|-------------------------------|-------------------------|
| GSH 138–01–94.....| 0.1     | 93.3                     | 8.0                           | 5.9                     |
| GSH 90+03–99.......| 1.0     | 83.0                     | 11.6                          | 4.9                     |
| GSH 90+03–99.......| 0.1     | 44.7                     | 6.3                           | 5.2                     |
|                  | 1.0     | 39.8                     | 9.1                           | 4.3                     |

Note.—Here $\zeta$ is the ratio of metallicity to the solar value, $R_{\text{merge}}$ is the maximum radius of an SNR before it disappears, assuming the explosion energy is $10^{51}$ ergs, $E_0$ is the explosion energy required when the observed radius of the object is equal to $R_{\text{merge}}$, and $d_{\text{max}}$ is the distance to the object if it is due to a single SNR with an explosion energy of $10^{51}$ ergs.

We reported the detection of an expanding hydrogen shell (GSH 90+03–99) most likely powered by a group of massive stars in its center. We interpret GSH 138–01–94, recently discovered by Stil & Irwin (2001), as another example of an SN/OB-association-powered bubble at a large distance. We think that this is a common phenomenon, and we expect the detection of similar objects in the future.

The size of GSH 90+03–99 is 110 $\times$ 220 pc at a distance of 13 kpc. It contains $10^5 M_\odot$ of neutral material and is expanding at 15 km s$^{-1}$. This gives a kinetic energy of $2.3 \times 10^{50}$ ergs. If OB associations are sufficiently distant, it becomes difficult to detect the optical emission from their members. In this case, atomic and molecular gas are their best tracers, and a survey with high angular resolution, covering a large area of the Galactic plane is ideal for their detection. Spectral information is decisive in distinguishing the SNRs from H ii regions; but at large distances, due to low surface brightness, this information is usually unavailable. Therefore, the energetics of the observed structures become important to characterize these objects. H ii, being unaffected by interstellar absorption, is an easily detectable tracer of objects at large distances and is also very efficient for the study of their kinematics.

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