AN OLD SUPERNOVA REMNANT WITHIN AN H\textsc{ii} COMPLEX AT $\ell \approx 173^\circ$: FVW 172.8+1.5

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ABSTRACT

We present the results of H\textsc{i} 21 cm line observations to explore the nature of the high-velocity (HV) H\textsc{i} gas at $\ell \sim 173^\circ$. In low-resolution H\textsc{i} surveys this HV gas appears as faint, wing-like, H\textsc{i} emission that extends to velocities beyond those allowed by Galactic rotation. We designate this feature as Forbidden Velocity Wing (FVW) 172.8+1.5. Our high-resolution (3\textdegree 4) Arecibo H\textsc{i} observations show that FVW 172.8+1.5 is composed of knots, filaments, and ring-like structures distributed over an area of a few degrees in extent. These HV H\textsc{i} emission features are confined within the limits of the H\textsc{ii} complex G173+1.5, which is composed of five Sharpless H\textsc{ii} regions distributed along a radio continuum loop of size 4\textdegree 4 x 3\textdegree 4, or $\sim 138$ pc x $107$ pc, at a distance of 1.8 kpc. G173+1.5 is one of the largest star-forming regions in the outer Galaxy. We demonstrate that the HV H\textsc{i} gas is well correlated with the radio continuum loop and that the two seem to trace an expanding shell. The expansion velocity of the shell is large (55 km s$^{-1}$), suggesting that it represents a supernova remnant (SNR). We derive physical parameters for the shell and show these to be consistent with the object being an SNR. We also detect hot X-ray-emitting gas inside the H\textsc{ii} complex by analyzing the ROSAT all-sky X-ray background survey data. This also supports the SNR interpretation. We conclude that the HV H\textsc{i} gas and the X-rays are most likely the products of a supernova explosion(s) within the H\textsc{ii} complex, possibly in a cluster that triggered the formation of these H\textsc{ii} regions.

Key words: H\textsc{ii} regions – ISM: individual objects (FVW172.8+1.5) – ISM: supernova remnants – radio lines: ISM – stars: formation

Online-only material: color figures

1. INTRODUCTION

In large-scale ($\ell$, $v$) diagrams of H\textsc{i} 21 cm line emission in the Galactic plane, there are many small, faint, high-velocity (HV) “wing-like” features extending to velocities well beyond the maximum or minimum permitted by Galactic rotation (Koo & Kang 2004). These “Forbidden Velocity Wings (FVWs)” are likely due to energetic phenomena in the Galaxy, as they are confined to small areas ($\lesssim 2^\circ$) and project smoothly beyond the general Galactic emission to high velocities. Koo & Kang (2004) suggested that some of these FVWs may represent the expanding shells of “missing” supernova remnants (SNRs), which are not included in existing SNR catalogs. The basic idea is that old SNRs are faint in the radio continuum, making it difficult to identify them because of both the confusion due to the Galactic background emission and observational limitations (e.g., Brogan et al. 2006). Koo & Kang (2004) considered the fact that an old SNR should possess a fast-expanding H\textsc{i} shell that will still be present as a coherent entity after the remnant becomes too faint to be visible in the radio continuum. If its expansion velocity is greater than the minimum or maximum velocities permitted by Galactic rotation, then an old SNR shell, or part of it (maybe the caps), could be detected as HV H\textsc{i} gas, e.g., FVWs. Indeed, Koo et al. (2006) have carried out high-resolution H\textsc{i} line observations toward one FVW and detected a rapidly expanding (80 km s$^{-1}$) H\textsc{i} shell, the parameters of which are consistent with those of the remnant of an SN that exploded some 0.3 Myr ago.

Recently, Kang & Koo (2007) identified 87 FVWs from the Leiden/Dwingeloo H\textsc{i} survey (Hartmann & Burton 1997) and the Southern Galactic Plane Survey data (McClure-Griffiths et al. 2005). Among these, six FVWs are found to be coincident with SNRs, four with nearby galaxies, and three with HV clouds. The rest (85%) are not associated with any obvious objects that could be responsible for their high velocities. We have since been making follow-up high-resolution H\textsc{i} observations of these FVWs of unknown nature using the Arecibo 305 m and Green Bank 100 m radio telescopes in order to identify their natures and origins, and have now observed $\sim 30\%$ of them. We find that about 40% of the observed FVWs have shell-like morphologies. More than half of these are apparently expanding at $\gtrsim 50$ km s$^{-1}$, which supports the possibility of some FVWs being old SNRs. The other 60% show irregular structures consisting of filaments and clumps. Most of these show faint bumps in their line profiles indicating HV H\textsc{i} clouds. They might correspond to the fast-moving, compact clouds in the disk, or in the disk–halo interface, that have been recently detected in sensitive, high-resolution H\textsc{i} surveys (Stanimirović et al. 2006; Begum et al. 2010, and references therein). The full results from our survey will be presented in a separate paper.

Here, we report Arecibo H\textsc{i} 21 cm line observations of FVW172.8+1.5. This particular FVW is unique in that it is associated with an H\textsc{ii} complex in the outer Galaxy. We show that FVW 172.8+1.5 is most likely an old SNR produced in this complex. The catalog of Kang & Koo (2007) lists this feature as two objects, FVW173.0+0.0 and FVW173.0+3.0. However, the Arecibo H\textsc{i} image shows that these are likely to be parts of a single coherent object, which we will call FVW172.8+1.5. In Section 2, we describe the H\textsc{i} observations.
Figure 1. \textit{H\textsc{i}} channel images of the observed field. Each image is integrated over a velocity interval of 5.1 km s$^{-1}$. The central LSR velocity is given at the bottom left of each image. The numbers in the brackets are the minimum and maximum brightness temperatures (K) of the gray scale which is linear. The black cross indicates the approximate center of the \textit{H\textsc{i}} structure. The dotted ellipse on the +24.7 km s$^{-1}$ frame marks the boundary of the proposed shell as adopted in this paper.

The \textit{H\textsc{i}} results are presented in Section 3. In Section 4, we present a multi-wavelength view of the \textit{H\textsc{ii}} complex in this region and investigate its association with FVW172.8+1.5. We discuss the origin of FVW172.8+1.5 and the star formation history in this area in Section 5, presenting a summary in Section 6.

2. THE \textit{H\textsc{i}} 21 cm LINE OBSERVATIONS

The \textit{H\textsc{i}} 21 cm line observations of FVW172.8+1.5 were made in 2006 October with the Arecibo 305 m telescope using the seven-beam, dual-polarization, Arecibo \textit{L}-band Feed Array (ALFA). The beam-to-beam spacing for the scanning pattern used was 1.8. GALSPECT, a dedicated spectrometer for Galactic \textit{H\textsc{i}} ALFA surveys, was used as the back end. Both wide- and narrowband spectra were acquired (see Stanimirović et al. 2006 for details). Here, we present the data from the narrower 7.14 MHz band, which is analyzed into 8192 equally spaced channels, giving an unsmoothed velocity resolution of 0.18 km s$^{-1}$.

The field observed covers an area of $7.5 \times 4.5$ centered at $(\alpha, \delta) = (5^h37^m, 35^\circ 30')$ (J2000). The observations employed the basket-weaving technique (Peek & Heiles 2008; Peek et al. 2007), which scans the sky with a zig-zag pattern by driving the telescope up and down on the prime meridian at a speed of 1.5 arcmin s$^{-1}$. For bandpass correction, a “Least-Squares Frequency Switching” (Heiles 2007) calibration was performed each day. Data reduction used the IDL pipe-line codes developed by the Berkeley group (Peek & Heiles 2008). Using these, the data were converted into a brightness temperature cube. The contamination due to the coma sidelobes of the ALFA off-center beams has been corrected (see Peek & Heiles 2008 for the details of data reduction). The final cube has a velocity resolution of 0.74 km s$^{-1}$, a spatial half-power beam width of 3.4 arcmin, and an rms of 0.13 K.

3. THE \textit{H\textsc{i}} RESULTS

Figure 1 shows channel images of the Arecibo \textit{H\textsc{i}} data. The \textit{H\textsc{i}} emission associated with FVW172.8+1.5 is visible for $+19.5 \text{ km s}^{-1} \lesssim v_{\text{LSR}} \lesssim +50.4 \text{ km s}^{-1}$. At the highest velocities ($+40.1 \text{ km s}^{-1} \lesssim v_{\text{LSR}} \lesssim +50.4 \text{ km s}^{-1}$), the \textit{H\textsc{i}} appears to be largely separated into two concentrations centered at $(5^h37^m, 36^\circ 30')$ and $(5^h27^m, 34^\circ 30')$. These were previously designated FWV173.0+3.0 and FWV173.0+0.0, respectively. The northern concentration (FWV173.0+3.0) looks diffuse and clumpy and appears to form a ring-like structure with a diameter of $\sim 2^\circ$. In contrast, the southern concentra-
Figure 2. Three-color image showing the Arecibo H\textsc{i} emission from FVW172.8+1.5. Red, green, and blue represent the images integrated over LSR velocities of +45 to +35, +35 to +25, and +25 to +20 km s\textsuperscript{-1}, respectively. Effelsberg 11 cm radio continuum contours (Fürt et al. 1990) are overplotted. Contour levels are 30, 100, and 200 mK in brightness temperature.

(A color version of this figure is available in the online journal.)

Figure 3. H\textsc{i} peak brightness temperature over the range of Galactic longitude, 171.8–173.7, as a function of Galactic latitude. In order to show H\textsc{i} features at lower velocities, the intensity scale for brightness temperatures in excess of 5 K is greatly expanded. The gray-scale ranges are shown by the bar in the upper right of the figure; values for brightness temperatures <5 K are marked below the bar, with those for >5 K are marked above. The merit of a peak intensity image is that it enhances bright structures that would not be seen in an averaged image.

The various H\textsc{i} features described above are also visible in Figure 2, which is a three-color image of the H\textsc{i} gas integrated over different velocity intervals. In this figure, we superpose the Effelsberg 11 cm radio continuum contours (Fürt et al. 1990). It is seen that the HV H\textsc{i} emission features lie essentially within the radio continuum filaments. The northwestern HV H\textsc{i} gas, represented by red and green colors, is confined within the northern part of the continuum structure, while the H\textsc{i} features at lower velocities (colored blue) lie along the inner boundary of the outer radio continuum filaments. The morphological relation between the H\textsc{i} and the radio filaments strongly suggests their association. In addition, there is little possibility of chance alignment of the two structures, because confusion is low along the line of sight (LOS) in the direction of \(\ell \sim 173^\circ\). The increase of the surface area and/or the size of the H\textsc{i}-emitting region with decreasing velocity suggests that we are looking at the receding portion of an expanding shell. The H\textsc{i} morphology does not exactly match that of a uniformly expanding spherical shell, but this could be due to a non-uniform and inhomogeneous ambient ISM. The radio continuum structure is part of the H\textsc{ii} complex in this area, and we will investigate the association of the two at other wavelengths in Section 4 and their physical properties and origin in Section 5.

The velocity structure of the HV H\textsc{i} features is shown in Figure 3, which shows the peak H\textsc{i} brightness temperature in
Galactic longitude as a function of Galactic latitude and velocity. This position–velocity diagram shows the HV gas over the entire field in a single diagram and enhances the appearance of small-scale wing-like features. Figure 3 shows that FVW172.8+1.5 is composed of many small-scale, HV wings spatially confined to $-1^\circ < b < +4^\circ$, which suggests an inhomogeneous nature for the shell. These wings are mostly straight but some have the shape of an extended ring, e.g., that at $b = -0^\circ.2$. This indicates that the shell is composed of small clumps. Since only the HV end portions of the wings are visible, their central velocities are usually not accessible. However, a few line profiles in the area near $(5^h34^m5, +36^\circ03')$ show discrete spectral features at high velocities (Figure 4). A Gaussian fit to these features results in a central velocity of $+33$ to $+35$ km s$^{-1}$ and a velocity dispersion of $4.3$–$6.4$ km s$^{-1}$, corresponding to kinetic temperatures of 2200–4900 K if the broadening is entirely due to thermal motions.

4. THE $\ell = 173^\circ$ REGION IN MULTI WAVEBANDS

4.1. Radio Continuum

4.1.1. The H II Complex G173+1.5

The region of Auriga within which FVW172.8+1.5 lies is an H II complex composed of Sharpless H II regions and OB associations in the Perseus arm (Figure 5). The H II regions
are organized along a large (∼7° × 4°) filamentary structure resembling a bow tie (Kerton et al. 2007). The H II regions have been studied previously (e.g., Israel & Felli 1978), and they are largely at two different distances (see Table 1). To the northeast of the structure, S231, S232, S233, and S235 are known to be associated with a giant molecular cloud at a distance of 1.8 kpc (Evans & Blair 1981), with CO radial velocities of −18.1 to −23.0 km s⁻¹ (Blitz et al. 1982), in which active star formation is ongoing (see Section 4.3). The distances determined by the photodetachment of the exciting stars of individual H II regions range from 1.0 to 2.3 kpc, but the distance to the associated molecular cloud (1.8 kpc) is often adopted as the distance to the whole H II complex. To the south of the complex, two 1° sized H II regions, S229 (IC 405) and S236 (IC 410), and the large (∼5°) diffuse H II region S230 are present. S236 is associated with a molecular cloud at ∼7.2 km s⁻¹ and might be at a considerably greater distance because the estimated distance to its central star cluster (NGC 1893) ranges from 3.2 to 6 kpc (Sharma et al. 2007 and references therein). For the other two H II regions (S229 and S230), not much has been known, although Fich et al. (1990) measured Hα velocities of +4.4 and 0.0 km s⁻¹ toward S229 and S230, respectively. Toward S229, CO J = 1–0 emission at +6.7 km s⁻¹ has been detected, but it may not be related to the H II region (Blitz et al. 1982). The small H II regions S234 (IC 417) and S237 in the middle of the “bow tie” have velocities of −13 and −4 km s⁻¹, similar to the first and second groups, respectively. A recent photometric determination of the distance to the central cluster (Stock 8) of S234 also agrees with the distance to the northwestern group of H II regions, i.e., 2.05 ± 0.10 kpc (Jose et al. 2008). We therefore consider that the Sharpless H II regions S231–S235 form the active star formation complex G173+1.5 at a distance of 1.8 kpc at vLSR ≈ 20 km s⁻¹. The other H II regions have considerably different velocities and distances, and they are not considered to be associated with this complex.

The morphology of the region suggests an association between the large radio continuum filamentary structures and the H II regions. Filaments A through D (see Figure 5) have similar concave shapes suggesting that they have resulted from a common source within the H II complex. For the radio Filament A, we have found an H I filamentary structure along the radio feature at vLSR = −25 to −28 km s⁻¹ (Figure 6). The correlation is not perfect in the sense that the H I feature looks less curved than the continuum filament and seems to extend outside of the field shown in Figure 6. However, the velocity is close to the CO velocity of S232, and the two could be associated. We could not find any H I structures associated with the other continuum filaments. Filament E has an enhanced brightness and its curvature is opposite to those of Filaments A–D. It is likely that the enhanced brightness and the convex shape is due to interaction with a dense ambient medium there, although no responsible molecular cloud is seen in the available CO survey data (Dame et al. 2001; see also Figure 9). Hence, Filaments A–E are likely to be associated with the H II complex G173+1.5, although we have only circumstantial evidence, except perhaps for Filament A. Kinematic evidence is needed to confirm the association.

### 4.1.2. The Radio Continuum Spectrum of Filament A

The nature of the radio emission from the large continuum filamentary structure has been discussed previously, although not in detail. Kerton et al. (2007) noted this structure in the 1420 MHz Canadian Galactic Plane Survey (CGPS) map, and argued that Filaments D and E are thermal emission based on the presence of corresponding infrared emission and/or the rising spectrum between 408 and 1420 MHz. Gao et al. (2010) claim that Filament A shows a thermal spectrum between the higher frequencies of 1.4 and 5 GHz.

Using radio continuum data from 325 MHz to 2.7 GHz available online (Table 2), we have attempted a study of the continuum spectrum of the filaments associated with the structure. The faint filamentary features are visible at most of these frequencies. Here we will focus on Filament A at (ℓ, b) ~ (172°5, +3°5), which stands out at 325 MHz in WENSS. To estimate values of spectral index, we (1) converted the WENSS data to brightness temperature, thus bringing all surveys to the same intensity units; (2) convolved all images to have a circular beam of FWHM = 47′, the declination beam size of the CGPS 408 MHz image at δ = 37°; (3) gridded the images onto the 2′ spaced pixels of the Effelsberg data; and (4) subtracted out all point sources. The final images are shown

### Table 1

| Name | R.A., Decl. (J2000) | Diameter   | vLSRb  | vLSRc  | Distancea |
|------|---------------------|------------|--------|--------|-----------|
|      | (h m, s)            | (′)        | (km s⁻¹)| (km s⁻¹)| (kpc)     |
| S229 | 5 16.3, +34 27      | 65         | +4.4   | +6.7   | 0.51      |
| S230 | 5 22.5, +34 08      | 300        | +0.0   | ...    | ...       |
| S231 | 5 39.3, +35 56      | 12         | −17.5  | −18.1  | 2.3       |
| S232 | 4 25.2, +36 12      | 40         | −13.7  | −23.0  | 1.0       |
| S233 | 5 38.7, +35 48      | 2          | −14.5  | −18.4  | ...       |
| S234 | 5 23.1, +34 26      | 12         | −14.3  | −13.4  | 2.3       |
| S235 | 5 41.0, +35 51      | 10         | −25.7  | −18.8  | 1.6       |
| S236 | 5 22.6, +33 22      | 55         | −3.8   | −7.2   | 3.2       |
| S237 | 5 31.4, +34 17      | 7          | +1.4   | −4.3   | 1.8       |

### Notes.

a Optical size (Sharpless 1959).
b Hα emission line radial velocity (Fich et al. 1990).
c CO radial velocity (Blitz et al. 1982). For S229, the association is uncertain.
d Distance determined by spectrophotometry of the central exciting star. See the references in Blitz et al. (1982).

![Figure 6. H I map integrated from vLSR = −28 to −25 km s⁻¹, with the 11 cm continuum contours overlaid. An H I filament along the continuum Filament A is visible (cf. Figure 5), although the correlation is not perfect.](image-url)
in Figure 7, where the dotted and solid boxes mark Filament A and the H\textsc{ii} region, S232, which provides a reference with a thermal spectrum. Finally, we removed a smooth, linear, large-scale background emission gradient using two neighboring areas, marked by pairs of boxes flanking the H\textsc{ii} region and the filament in Figure 7.

The continuum spectra of Filament A and S232 are shown in Figure 8 (left) by filled and open circles, respectively. The total flux densities are given in Table 3. The error bars in Figure 8 represent standard deviations in the neighboring areas after the removal of smooth backgrounds. Using all flux density values from 325 to 2695 MHz, the estimated spectral index ($S_\nu \propto \nu^{-\alpha}$) of S232 is $\alpha = -0.09 \pm 0.02$, while that of Filament A is $\alpha = +0.23 \pm 0.06$. We also derived spectral indices for Filament A and S232 using $T$–$T$ plots (Turtle et al. 1962). The regions used for making the $T$–$T$ plots are those over which the total flux densities were derived. Figure 8 (right) shows a $T$–$T$ plot between 325 and 2695 MHz of Filament A. The points are well described by a linear fit. The slopes of the plots, and the values of $\alpha$ derived between different pairs of frequencies, are summarized in Table 4. For S232, the derived spectral indices are consistent, ranging from $\alpha = -0.04$ to $+0.09$ which, together with the total flux density spectral index of $\alpha = -0.09$, is reasonably close to the value of $\alpha = +0.1$ expected for an optically thin thermal source. However, the spectral indices derived for Filament A are not straightforward to interpret. The frequency pairs that include 325 MHz result in $\alpha = +0.50 \pm 0.11$ and $+0.32 \pm 0.06$, consistent with non-thermal emission, while the pairs that include 408 MHz yield $\alpha = +0.07 \pm 0.10$ and $-0.04 \pm 0.08$, compatible with thermal emission. These trends are consistent with the plot of the total flux densities (Figure 8, left). In that plot, if either the 325 MHz or the 408 MHz data point is excluded, then the spectral index of Filament A would, respectively, be flatter or steeper than the $\alpha = +0.23 \pm 0.06$ derived using data at all frequencies.

As mentioned at the beginning of this section, previous studies claimed that the radio emission from some of these filaments is of thermal origin. However, our analysis in this section indicates the presence of a non-thermal component in Filament A. The fact that the spectral index of S232, as derived from the same

Table 2
Parameters of the Continuum Surveys Used for Spectral Analysis

| Name       | Frequency (MHz) | Resolution       | rms (mK) | References          |
|------------|-----------------|------------------|----------|---------------------|
| WENSS      | 325             | 54\arcsec 44\arcsec \csc \delta | 2300     | Rengelink et al. (1997) |
| CGPS       | 408             | 2/8 \times 2/8 \csc \delta | 950      | Taylor et al. (2003)  |
| CGPS       | 1420            | 49\arcsec 49\arcsec \csc \delta | 68       | Taylor et al. (2003)  |
| Effelsberg | 11 cm           | 43              | 20       | Fürst et al. (1990)   |

Figure 7. WENSS 325 MHz (top left), CGPS 408 MHz (top right), CGPS 1420 MHz (bottom left), and Effelsberg 2695 MHz (bottom right) radio continuum images of the northern part of the FVW173+1.5 field. The areas used to derive the total flux density and to plot $T$–$T$ diagrams of radio continuum Filament A and the H\textsc{ii} region, S232, are marked by thick dotted and solid boxes, respectively. The neighboring areas used for the subtraction of the large-scale background are marked by thin dotted and solid boxes. The white holes in the images are where point sources have been subtracted.
data, is consistent with optically thin thermal emission supports our result. Therefore, it is more likely that the filament has both thermal and non-thermal components (see also Section 4.3). If thermal and non-thermal components coexist in the filament, a steep spectrum at lower frequencies, and a flat spectrum at higher frequencies (as found by Gao et al.), might be expected. Also, if thermal and non-thermal components coexist in the continuum emission of Filament A, this could be the case for Filaments B–E. We have examined the polarization maps of this area. The G173 complex region was covered by the polarization surveys at 1.4 and 5 GHz (Landecker et al. 2010; Gao et al. 2010). While the 1.4 GHz polarization data of Landecker et al. do not show any apparent counterparts to the G173 structure, the 5 GHz polarization data of Gao et al. do show some filamentary features associated with the structure. In the polarized intensity map of Gao et al. (their Figure 17), two depolarized filaments, indicating a thermal nature, are recognizable; one at $(\ell, b) \sim (174.3, +2.0)$, which corresponds to Filament B, and the other at $(171.0, +2.5)$, located between Filaments A and D. Other than B, the continuum filaments have no apparent counterparts in this image. Hence, it is difficult to discuss the nature of Filaments A–E using the current polarization data, with the exception that a thermal component appears to dominate in Filament B. The nature of the continuum filaments needs to be investigated with more sensitive full-Stokes continuum data.

4.2. X-Rays

In the ROSAT Survey Diffuse X-ray Background Map (Snowden et al. 1997), there is faint, extended X-ray emission projected against the H II region G173+1.5. (Figure 9, top frames). The emission is mainly from two regions, one within the S231–S235 complex and the other associated with S229/S236. The emission is not visible in the soft band (1/4 keV) but appears at the hard bands (3/4 and 1.5 keV). This is consistent with the emission being associated with G173+1.5, because if we adopt $A_V = 1.2$ mag (or $N(H) = 2.3 \times 10^{21} \text{cm}^{-2}$) corresponding to the extinction to S234 (Jose et al. 2008) as the extinction to G173+1.5, the transmission of 1/4 keV photons is essentially zero ($<10\%$) while it is 40% and 80% at 3/4 and 1.5 keV, respectively (Seward 2000). The emission is not uniform and the ratio of 1.5 to 3/4 keV intensities varies over the field. Note that, since the contributions from point sources have been removed from the map, the emission is from diffuse sources, although some compact sources might have been included, e.g., the bright spot near S234. For the present analysis, we simply derive the X-ray photon counts inside the solid ellipse marked in Figure 9. The background is estimated from the surrounding regions marked by the two dotted ellipses. The derived count rates over 8.8 deg$^2$ are $0.76 \pm 0.08$ counts s$^{-1}$ and $0.78 \pm 0.11$ counts s$^{-1}$ in 3/4 keV and 1.5 keV bands, respectively. The ratio of 1.5 keV to 3/4 keV is 1.0 $\pm$ 0.2. Using the model of Snowden et al. (1997), the ratio corresponds to either a power-law photon spectrum ($E^{-\alpha}$, where $E$ is energy) of index $\alpha \sim 4$ or thermal spectrum with temperature of $\sim 10^6$ K for $N(H) = 2.3 \times 10^{21} \text{cm}^{-2}$. The power-law index 4 is considerably steeper than that of a pulsar wind nebula, e.g., $\sim 2$ for the Crab nebula, so that we may rule out a non-thermal
origin. The diffuse extended morphology also supports a thermal origin. According to Snowden et al. (1997), the attenuated count rate of thermal X-ray emission from $10^{6.9}$ K gas at 3/4 keV is $\approx$0.01 counts s$^{-1}$ arcmin$^{-2}$ for an emission measure (EM) of 1 cm$^{-6}$ pc. Therefore, the observed average 3/4 keV band count rate of $2.4 \times 10^{-5}$ counts s$^{-1}$ arcmin$^{-2}$ implies an average EM of 0.0024 cm$^{-6}$ pc. If we use $4R/3$, where $R = 60$ pc is the geometrical mean radius of the shell, as the mean depth along the LOS, then the mean electron density is about $5.5 \times 10^{-3}$ cm$^{-3}$. This implies a thermal energy for the X-ray-emitting gas of $\sim 3 \times 10^{50}$ erg, assuming that it fills the entire interior of the shell. If instead the X-ray-emitting gas fills only parts of the shell interior, then the thermal energy will be somewhat smaller than this. The derived thermal energy is close to that of an old SNR, which, together with the high temperature, suggests that the hot gas might have originated from an SN explosion within the H II complex G173+1.5.

4.3. Hα and CO

The radio continuum structure of G173+1.5 has counterparts in Hα. Figure 9 (bottom left) is the Hα full-sky map (6’ FWHM resolution) composite of the Virginia Tech Spectral line Survey (VTSS), the Southern Hα Sky Survey Atlas, and the Wisconsin H-Alpha Mapper survey (Finkbeiner 2003). In the northern area covered by the VTSS Hα image (Dennison et al. 1999), delicate Hα filaments are clearly visible, well correlated with the radio continuum filaments. If we compare in detail, however, there is a slight shift between the radio and Hα filaments; the Hα emission peaks at slightly lower latitudes, i.e., slightly inside the complex (Figure 10). If the radio feature is due to thermal emission, then the ratio of the two intensities are roughly constant as both depend on the EM. Using the formulae given in Spitzer (1978), the Hα intensity from ionized gas at 10,000 K is given by

$$I(\text{Hα}) \approx 0.36(n_p/n_e)EM \text{ Rayleigh},$$

where EM $= \int n_p^2 ds$ (cm$^{-6}$ pc), and $n_p$ and $n_e$ are proton and electron densities, respectively. The corresponding radio brightness temperature at 11 cm, using the formulae from Draine (2011), is $T_b \approx 0.40 \times 10^{-3}(n_p/n_e)EM$ K. Therefore, we have $T_b/I(\text{Hα}) \approx 4 \times 10^{-3}$ K R$^{-1}$ adopting an extinction of $A_V = 1.4$ mag. At $T = 5000$ K, this ratio would be slightly lower. Since the Hα intensity is normalized by 20 R and the 11 cm brightness is normalized by 0.1 K, the thermal 11 cm emission would have a comparable ($\sim 0.8$) normalized intensity in Figure 10. In fact, Figure 10 shows that at the Hα peak positions this is
normalized by 20 R and 0.1 K, respectively. integrated over v
distributions of H
maxima, the 11 cm brightness is considerably greater than the indeed the case. On the other hand, at the radio continuum
maxima, the 11 cm brightness is considerably greater than the H\text{\alpha} intensity, which implies a non-thermal origin. Therefore, the 11 cm continuum emission appears to be composed of both thermal and non-thermal components, which is consistent with our conclusion from the previous section.

Figure 9 (bottom right) shows the CO J = 1–0 intensity map integrated over v_{\text{LSR}} = −25 to −15 km s\(^{-1}\) (Dame et al. 2001). There is one giant molecular cloud at (\ell, b) \sim (173\degree, 2\degree). Four H\text{\i} regions, S231, S232, S233, and 235, are clustered around this molecular cloud. CO observations of this cloud show close positional correlations between the optical H\text{\i} regions and the molecular cloud (Heyer et al. 1996). The giant molecular cloud appears as interconnected filaments with bright CO emission located at the projected optical edges of S235 and S232. S233 lies within a void in the CO emission, implying complete ionization and photodissociation of the molecular material. It has been known that active star formation is ongoing around these H\text{\i} regions, and that jets and outflows from young stellar objects have been observed in molecular lines (e.g., Shepherd & Watson 2002; Beuther et al. 2002).

5. DISCUSSION

5.1. The Origin of FVW172.8+1.5

Our results indicate that the fast-moving H\text{\i} gas in FVW172.8+1.5 is confined within the H\text{\i} complex G173+1.5 and has a good spatial correlation with the radio continuum structure. This strongly suggests that its origin lies within the complex. Morphological association between the H\text{\i} emission and the continuum/H\text{\alpha} filaments further suggests that they probably trace the same object, i.e., an expanding shell. The X-rays detected within the complex may also be associated with this shell. In this section, we first derive the parameters that an expanding shell would possess, and then explore its possible origin. We take the systemic velocity and distance of both the H\text{\i} complex and FVW172.8+1.5 to be v_{\text{sys}} \approx −20 km s\(^{-1}\) and 1.8 kpc.

5.1.1. The Parameters of FVW172.8+1.5 as an Expanding Shell

The total extent of the putative shell based on the radio continuum filaments and our H\text{\i} observations is 4\textdegree.4 \times 3\textdegree.4, which converts to 138 pc \times 107 pc at 1.8 kpc. If we adopt the velocity centers of the highest-velocity clumps given in Section 4 (+35 km s\(^{-1}\)) as an endcap velocity of the shell, its expansion velocity is 55 km s\(^{-1}\). To derive the total H\text{\i} mass and kinetic energy of the FVW172.8+1.5, we need to estimate the total mass of the expanding shell. This can be done by extrapolating the mass distribution we derive for high velocities. Figure 11 shows the distribution of H\text{\i} mass in each 2.2 km s\(^{-1}\) velocity interval between v_{\text{LSR}} = +14 and +46 km s\(^{-1}\). We assume the receding and approaching hemispheres of the expanding shell

Figure 10. Left: an enlarged view of the Filament A in the VTSS H\text{\alpha} image with the 11 cm radio continuum contours superposed. Right: one-dimensional intensity distributions of H\text{\alpha} (dotted lines) and 11 cm continuum (solid lines) emission along Galactic latitudes at several Galactic longitudes. H\text{\alpha} and continuum intensities are normalized by 20 R and 0.1 K, respectively.

Figure 11. Mass distribution for the putative H\text{\i} shell assuming a distance of 1.8 kpc. The filled circles are the derived H\text{\i} masses for each 2.2 km s\(^{-1}\) velocity interval. The error bars show the standard deviation for the background area. The solid line shows a Gaussian fit to the data, while the dotted line shows the best fit for the mass distribution of a shell with a constant v_{\text{exp}} = 55 km s\(^{-1}\) and v_{\text{exp}} = 5.5 km s\(^{-1}\), and the dashed line shows the best fit for the mass distribution of a shell with a velocity dispersion v_{\text{disp}} = 5.5 km s\(^{-1}\), but whose expansion velocity at the outer radius of the shell drops linearly to 50% of the expansion velocity at the inner radius.
to be symmetric and centered at $v_{\text{LSR}} = -20$ km s$^{-1}$. Note that the approaching portion of the shell is not visible because of confusion by the Galactic background/foreground H$\text{I}$ emission. While this may not be true, the resulting kinetic energy would be roughly correct should the energy injection be spherically symmetric. A Gaussian shape is often used for the extrapolation when fitting the mass distribution of the observed H$\text{I}$ shells (e.g., Giovanelli & Haynes 1979; Koo et al. 1990, 2006). If we adopt this Gaussian extrapolation (the solid line in Figure 11), we obtain a value of $1.3 \times 10^7 d_{1.8 \text{kpc}}^2 M_\odot$. However, this may overestimate the total mass because for an ideal expanding thin shell of uniform density, the mass per unit radial velocity interval is constant. The mass profile at the highest velocities could be decreasing due to the velocity dispersion, or the velocity structure, within the shell. However, the mass profile at the central velocities would remain constant unless the turbulent velocity in the shell were large enough to be comparable to its expansion velocity.

Here, we develop a simple, but physical, shell model that yields a flat mass profile for the central velocities. We consider a spherical shell with a radius $R = 2'$, a thickness $\Delta R = 10'$, an expansion velocity $v_{\text{exp}} = 55$ km s$^{-1}$, and a dispersion velocity $v_\sigma = 5.5$ km s$^{-1}$. These parameters are derived from the observed H$\text{I}$ shell. We assume that the gas density within the shell is constant. For the radial profile of expansion velocity within the shell, we consider two different cases. The first is that the expansion velocity is constant with radius. The second is that the expansion velocity varies linearly with radius. Linearly decreasing or increasing velocity structures within the shell are derived by theoretical studies for different ages of radiative shells (Slavin & Cox 1992; Blondin et al. 1998). Here, we choose a velocity structure for which the expansion velocity at the outer radius drops to 50% of that at the inner radius.

To fit the derived mass distribution, we adopt a three-dimensional cube composed of 451$^3$ pixels. The $z$-axis is along the LOS. The number density of H$\text{I}$ atoms for a pixel centered at $r = (x^2 + y^2 + z^2)^{1/2}$ is $n(r)$, which is assumed to be constant in our model. This pixel has an LOS velocity $v_{\text{LOS}}(x, y, z) = v_{\text{exp}}(r)/r$, where $v_{\text{exp}}(r)$ is the radial expansion velocity at $r$. The H$\text{I}$ 21 cm emission line from this pixel has a Gaussian distribution with the LOS velocity dispersion of $v_\sigma (=5.5$ km s$^{-1}$). Then the column density, $N(x, y, v)$, at $(x, y)$ over the LSR velocity interval from $v$ to $v + \Delta v$ and the H$\text{I}$ mass, $M(v)$, between $v$ and $v + \Delta v$, are given as follows:

$$N(x, y, v) = \frac{n}{\sqrt{2\pi v_\sigma^2}} \int_v^{v+\Delta v} \int \int \exp \left( \frac{-(v' - v_{\text{LOS}}(x, y, z))^2}{2v_\sigma^2} \right) dv'dz,$$

$$M(v) = m_{\text{H}} \int \int N(x, y, v) dx dy.$$

The dotted line in Figure 11 is the best fit for the mass distribution of a shell with a constant expansion velocity profile. Here, the only fitting parameter is the density of the shell. The velocity range, where the mass of the observed H$\text{I}$ shell smoothly decreases, is wider than the velocity range due to velocity dispersion, so the observed H$\text{I}$ mass distribution cannot be explained by velocity dispersion alone. The dashed line shows the best fit for the mass distribution of a shell with an expansion velocity profile linearly decreasing toward larger radii. This dashed line fits the observed mass better than the dotted line. Variation of the expansion velocity with radius dilutes the rectangular mass distribution at high velocities, but still yields a constant mass distribution at lower velocities, from $v_{\text{LSR}} \sim -50$ to $+10$ km s$^{-1}$. Note that the basic shape of the mass profile is determined by the difference between the minimum and maximum expansion velocities. The detailed velocity and density structures only affect the shape of the decreasing portion of the mass profile. We will study the mass profiles resulting from various velocity and density structures in a forthcoming paper. The estimated total H$\text{I}$ mass of the shell adopting a linearly decreasing velocity profile is $5900 d_{1.8 \text{kpc}}^2 M_\odot$. We will use this value as the characteristic mass of the shell. Note that the total mass derived from the Gaussian fit is about twice this. The kinetic energy of the shell, taking into account the He abundance of 10% by number, is $0.25 \times 10^{51} d_{1.8 \text{kpc}}^2$ erg. The derived physical parameters of the model H$\text{I}$/continuum shell are presented in Table 5.

| Parameter                  | Estimated Value |
|----------------------------|-----------------|
| Center ($\alpha, \delta$) | $05^h33^m29^s.4, +35^\circ50.52^\prime$ |
| Mean radius ($\ell, b$)   | $172^\circ78.8, +1^\circ51$ |
| Expansion velocity        | $69 \times 5 d_{1.8 \text{kpc}}$ pc |
| Total H$\text{I}$ mass    | $555 \pm 5$ km s$^{-1}$ |
| Total H$\text{I}$ mass    | $5900 \pm 770 d_{1.8 \text{kpc}}^2 M_\odot$ |
| Kinetic energy            | $0.25 \pm 0.05 \times 10^{51} d_{1.8 \text{kpc}}^2$ erg |
| Initial ISM density       | $0.25 \pm 0.03 d_{1.8 \text{kpc}}^2$ cm$^{-3}$ |
| Age                       | $3.33 \pm 0.03$ Myr |

Notes. The errors are 1$\sigma$ errors. For the estimation of the initial ISM density and age, we use the geometrical average of the mean radius ($61$ pc).

5.1.2. The Origin of FVW172.8+1.5 and the X-Rays

We can think of two possibilities for the origin of FVW172.8+1.5: stellar winds from OB stars or SN explosions. H$\text{II}$ regions can also produce expanding H$\text{I}$ shells, but their expansion velocities and energies are much smaller than those of FVW172.8+1.5. Furthermore, the H$\text{II}$ regions are mostly located at the boundary of the structure, so that they do not appear to be major sources of the 3$'$–4$'$ sized shell. We first consider whether the stellar winds from OB stars can produce FVW172.8+1.5. There are more than a dozen O stars in this area (Garmany et al. 1982; Maiz-Apellanz et al. 2004), with eight of them projected against the shell (Figures 5 and 9). We summarize the parameters of these stars in Table 6. Their spectral types range from O9.5 to O7, and four are associated with the Sharpless H$\text{II}$ regions. The other four could be possible candidates for the origin of the H$\text{I}$/continuum shell. If we use the relation of Howarth & Prinja (1989) and a wind speed of $\sim$2000 km s$^{-1}$, then the typical wind luminosities of O7–O9 main-sequence stars are $(5-0.8) \times 10^{35}$ erg s$^{-1}$. For giant O stars, this would be larger by a factor of two. However, the required wind luminosity to explain the parameters of the shell is $L_w = 77 E_K/(9 R/v_{\text{exp}}) = 6 \times 10^{37}$ erg s$^{-1}$ (Weaver et al. 1977), which is 2 orders of magnitude greater than the available wind luminosities. Even if there are groups of stars in this area (see the next section), their contribution to the wind luminosity will not be significant because they are no brighter than O9.

We thus consider that FVW172.8+1.5 is likely to be the result of an SN explosion. Certainly, the derived parameters are fully
Table 6

| Name       | R.A., Decl. (J2000) (h m, s) | Spectral Type | Distance (kpc) | Associated H II Region |
|------------|-------------------------------|---------------|---------------|-------------------------|
| HD 36483   | 5 33.8, +36 28                | O9 IV         | 1.3           | ...                     |
| HD 39291   | 5 29.8, +35 20                | O9.5 III      | 1.3           | ...                     |
| LS V+35 24 | 5 39.7, +35 53                | O9V           | 2.1           | S231                    |
| BD+35 1201 | 5 41.0, +35 50                | O9.5V         | 1.6           | S235                    |
| HD 37737   | 5 42.4, +36 09                | O9.5 III      | 1.3           | S232                    |
| BD+34 1058 | 5 28.4, +34 40                | O8            | 3.2           | ...                     |
| HD 35619   | 5 27.5, +34 47                | O7 V          | 3.2           | ...                     |
| BD+34 1054 | 5 28.1, +34 25                | O9.5 V        | 2.0           | S234                    |

Notes. The O stars (Garmann et al. 1982; Maiz-Apellaniz et al. 2004) located within a radius of 2.5 from the center of the H I/continuum structure are listed in order of angular distance from the center. See also Figure 5. The distance of a star is computed from its distance modulus, assuming an interstellar absorption of A(V) = 3E(B − V) (Garmann et al. 1982).

consistent with this interpretation. The required SN explosion energy is $E_{SN} = 6.8 \times 10^{51} n_0 \rho_0 R_s v_{exp}^{1.35} \chi^{0.161}$ erg, where $n_0$ is the ambient H density in cm$^{-3}$, $R_s$ is the radius of the shell in pc, $v_{exp}$ is the expansion velocity in km s$^{-1}$, and $\chi$ is the metallicity in units of the solar metallicity (Cioffi et al. 1988). For the above parameters, $E_{SN} = 1.3 \times 10^{51}$ erg, where the solar metallicity has been adopted. This value of $E_{SN}$ is close to the canonical outburst energy of a single SN explosion of $1 \times 10^{51}$ erg. The age of the shell, assuming this to be in the radiative stage of SNR evolution, is $t = 0.3 R_s / v_{exp} = 0.33$ Myr. The SNR interpretation is also consistent with the presence of X-rays in this region. The thermal energy of the X-ray-emitting gas is $3 \times 10^{50}$ erg, which is 25% of the initial explosion energy and close to that expected for a 0.33 Myr old radiative SNR (e.g., Cioffi et al. 1988). The apparent segregation between the fast-moving H I gas and the X-ray-emitting gas could be due to a non-uniform and/or inhomogeneous density distribution in the ambient medium. It is also possible that more than one SN exploded within the past few $10^5$ yr. We have checked for known pulsars in this area, but none are known within the boundary of the putative shell. The nearest pulsar, PSR J0540+32 at $(\ell, b) = (176^\circ 80, +0^\circ 72)$, is $\sim 4^\circ$ distant from the center of the H I/continuum feature, and lies at a distance of $\sim 6.2$ kpc. PSR J0540+32 is thus unlikely to be associated with the progenitor of FVW1728+1.5.

5.2. Speculations on the Star Formation History of G173+1.5

The H II complex G173+1.5 is composed of five Sharpless H II regions S231–S235. Of these, all but S234 are clustered around a giant molecular cloud (Figure 9). There are at least 14 embedded star-forming clusters that are 3–5 Myr old around these four H II regions (Kirsanova et al. 2008; Dewangan & Anandarao 2011; Camargo et al. 2011, and references therein). S234, located $3^\circ$ below the other H II regions, also has an associated cluster with young stellar objects having an age of $\sim 3$ Myr (Jose et al. 2008). It has been proposed that the formation of some of these star-forming clusters could have been triggered by the first-generation stars in these H II regions.

The presence of an old SNR filling the H II complex G173+1.5 has an interesting implication. The five Sharpless H II regions are located within the boundary of the H I/continuum structure, suggesting that their formation could have been triggered by SN explosions, stellar winds, or expanding H II regions from a previous generation of stars (see Elmegreen 1998 for a review of triggered star formation). The age of the SNR for which we have found evidence is, however, only 0.33 Myr, so that it is not possible that the current expanding shell triggered the formation of these H II regions. Instead, it could be the cluster to which the SN progenitor belonged that triggered the formation of these H II regions. There are two stellar associations in this area: Aur OB1 at a distance of 1.3 kpc and Aur OB2 at 3.2 kpc (Humphreys 1978). We suspect that Aur OB1, which is scattered over a wide area, $(\ell = 168^\circ 1–178^\circ 1, b = -7^\circ 4–4^\circ 2)$, could be composed of several associations at slightly different distances. The distance moduli of Aur OB1 stars indeed range from 9.69 to 11.67 or 0.9 to 2.2 kpc in distance (Humphreys 1978). HD 36483 (O9 IV) and HD 39291 (O9.5 III) are relatively close to the central area of the H I/continuum structure and also belong to Aur OB1. If one, or both, of these also belonged to the appropriate cluster, then since the main-sequence lifetime of a $20 M_\odot$ O star is $\sim 8$ Myr (Schaller et al. 1992), the star formation in this area began $\geq 8$ Myr ago. In this scenario, the first-generation stars triggered the formation of a second generation that are currently exciting the Sharpless H II regions (S231–S235), and we are now observing the formation of third-generation stars around these H II regions. The H II complex G173+1.5 could be another good example of sequential star formation over several stellar associations.

6. SUMMARY

We have made high-resolution H I 21 cm line observations of a $7.5 \times 4.5$ area centered at $(\ell, b) = (173^\circ, -1^\circ 5)$ using the ALFA seven-beam receiver mounted on the Arecibo 305 m telescope. The data cube provides a detailed view of the fast-moving H I gas at velocities forbidden by Galactic rotation in this area. FVW1728+1.5 is a feature that appears as a faint wing in low-resolution surveys. By comparison with radio continuum, X-ray, and H$\alpha$ maps, we find evidence that FVW1728+1.5 is likely to be an old SNR within a large H II complex situated in this area. Our results are summarized as follows.

1. The H I emission associated with FVW1728+1.5 is visible from $v_{LSR} = +19.5$ to $+50.4$ km s$^{-1}$. At the highest velocities, the H I appears to be separated into two concentrations. At lower velocities, a thin, filamentary feature appears surrounding these two concentrations. The increase of the surface area and the amount of H I gas with decreasing velocity suggests that it is an expanding shell. We attribute the complex morphology to the non-uniformity and inhomogeneity of the ambient medium.

2. The HV H I emission features are confined inside the radio continuum filaments associated with the large H II complex G173+1.5 and show a very good spatial correlation with them. This strongly suggests that it has an origin within the complex. Adopting a distance of 1.8 kpc, and the systemic velocity of $\sim 20$ km s$^{-1}$ of the H II complex to be appropriate for the H I shell, we derive physical parameters for the shell. These yield a kinetic energy of $2.5 \times 10^{50}$ erg. This large kinetic energy and the fast-expansion velocity implies an SN origin.

3. We investigated the nature of the filaments in the H II complex G173+1.5 using multi-wavelength data. Our analysis of the radio continuum spectrum suggests that the radio filaments have both thermal and non-thermal components. A detailed comparison with the associated H$\alpha$ filament supports this conclusion. We also find X-ray-emitting hot gas inside the complex with an estimated thermal energy of...
3 \times 10^{50} \text{ erg}. This associated hot gas of comparable thermal energy to the kinetic energy of expansion, and the probable presence of non-thermal radio filaments, supports the conclusion that the H\textsc{ii} gas is of SN origin.

4. From our analysis, we conclude that FVW 172.8+1.5 is likely to be an old ($\sim$0.33 Myr) SNR produced inside the H\textsc{ii} complex G173+1.5. We propose that the stellar association to which the progenitor belonged could have triggered the formation of the OB stars currently exciting the H\textsc{ii} regions. The H\textsc{ii} complex G173+1.5 appears to be a potential example of sequential star formation over several stellar associations.

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