INVESTIGATION OF THE LARGE-SCALE NEUTRAL HYDROGEN NEAR 
THE SUPERNOVA REMNANT W28

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ABSTRACT

The distribution and kinematics of neutral hydrogen have been studied in a wide area around the supernova remnant (SNR) W28. A $2.5 \times 2.5$ field centered at $l = 6.5$, $b = 0^\circ$ was surveyed using the Parkes 64 m radio telescope (half-power beamwidth of 14.7 at 21 cm). Even though W28 is located in a complex zone of the Galactic plane, we have found different H$\text{I}$ features, which are evidence of the interaction between W28 and its surrounding gas. An extended cold cloud with about 70 $M_\odot$ of neutral hydrogen was detected at the location of W28 as a self-absorption feature, near the local standard of rest velocity of +7 km s$^{-1}$. This H$\text{I}$ feature is the atomic counterpart of the molecular cloud shown by previous studies to be associated with W28. From this detection, we can independently confirm a kinematical distance of about 1.9 kpc for W28. In addition, the neutral hydrogen observed in emission around the SNR displays a ringlike morphology in several channel maps over the velocity interval $[-25.0, +38.0]$ km s$^{-1}$. We propose that these features are part of an interstellar H$\text{I}$ shell that has been swept up by the supernova shock front. Emission from this shell is confused with unrelated gas. Hence, we derive an upper limit for the shell mass of 1200–1600 $M_\odot$, an age of $3.3 \times 10^4$ yr. The preexisting ambient medium has a volume density on the order of $1.5–2 \text{ cm}^{-3}$. W28 is probably in the radiative evolutionary phase, although it is not possible to identify the recombined thin neutral shell expected to form behind the shock front with the angular resolution of the present survey.

Key words: ISM: H$\text{I}$ — ISM: individual (W28) — ISM: structure — supernova remnants

1. INTRODUCTION

Each supernova remnant (SNR) is the unique product of its own history (the progenitor and the explosion mechanism) and the characteristics of the environs in which it evolves. The study of the interstellar medium around SNRs can be used to understand the appearance of a remnant in different spectral regimes (distorted shapes, local brightness enhancements, filamentary emission, etc.). Such studies also allow the analysis of the temporal evolution of SNRs. In addition, the investigation of the gaseous matter around SNRs can lead to an understanding of the Galactic interstellar medium. These studies are important in understanding the response of the interstellar gas to the large injection of energy and momentum that a supernova (SN) explosion represents.

Numerous investigations of interaction of SNRs with the surrounding interstellar medium (ISM) have been made using atomic and molecular lines (Routledge et al. 1991; Pineau et al. 1993; Wallace, Landecker, & Taylor 1994; Frail, Goss, & Slysh 1994; Frail et al. 1996; Frail & Mitchell 1998; Reynoso et al. 1995; Dubner et al. 1998a, 1998b). These investigations show the manner in which the expansion of a SN shock front modifies the surrounding environment and the effect that the surrounding gas has, in turn, on the shape and dynamics of the SNR. In the present study, we report the results of an H$\text{I}$ study around the SNR W28 (G6.4–0.1).

The SNR W28 is located in a very complex region of the Galaxy, near the large H$\text{II}$ regions M8 and M20 and the young clusters NGC 6530, NGC 6514, and Bo 14. It has a number of prominent morphological characteristics. In the radio continuum, there is diffuse emission, together with thin filaments and small bright regions, as seen in Figure 1. This image is the result of combining 50 Very Large Array (VLA) pointings into a 20 cm mosaic (Dubner et al. 2000). In X-rays, diffuse thermal emission fills the interior of W28, although ear-shaped segments of a limb-brightened shell can also be observed toward the northeast and northwest (Rho & Petre 1996). In the optical, there are bright narrow filaments strongly correlated with radio features and diffuse H$\alpha$ nebulosities, apparently anticorrelated with the radio synchrotron emission (Long et al. 1991; Dubner et al. 2000).
A number of observations support the existence of a physical interaction between W28 and an adjacent molecular cloud: (1) the existence of shocked CO and other molecular species (Wootten 1981; Frail & Mitchell 1998; Arikawa et al. 1999), (2) the detection of over 40 1720 MHz OH masers distributed along the brightest synchrotron features (Claussen et al. 1997, 1999), and (3) the coincidence of the molecular gas with the brightest synchrotron filaments, which are the features with the flattest spectral index in the SNR (as expected for high Mach number shocks; from Dubner et al. 2000). All these indicators point to the existence of an interaction between the SNR and the molecular cloud.

In what follows, we analyze the distribution of the neutral hydrogen around W28, based on a survey of the 21 cm H\textsubscript{i} line carried out for a field with the Parkes 64 m radio telescope.

2. OBSERVATIONS AND DATA REDUCTION

An area of 6.25 deg\textsuperscript{2}, centered at $l = 6^\circ 0$, $b = -0^\circ 5$ was observed using the Parkes 64 m telescope on 1995 June 23 and 24. The wide-band (1.2–1.8 GHz) receiver was used with orthogonal, linearly polarized feeds. The half-power beamwidth of the telescope at the frequency of the H\textsubscript{i} line is 14 arcmin, and the pointing accuracy is $\pm 20^\prime$. The system noise temperature is 28 K, measured against cold sky. Each polarization was recorded with an instantaneous bandwidth of 4 MHz over 2048 channels, giving a channel separation of 1.95 kHz (0.4 km s\textsuperscript{-1} at 1.4 GHz). The total velocity coverage is $\pm 400$ km s\textsuperscript{-1} centered at 0 km s\textsuperscript{-1} with respect to the local standard of rest (LSR). After Hanning smoothing, the velocity resolution per channel is 3.91 kHz (or 0.82 km s\textsuperscript{-1}).

In total, 289 positions were observed using constant Galactic latitude scans with an integration time of 50 s per spectrum. A reference spectrum for bandpass calibration was taken using frequency switching to $-400$ km s\textsuperscript{-1} at 25 minute intervals. Spectra were measured at the Nyquist sampling interval on a 7.5 grid.

Flux density calibration was made using scans across Hydra A, for which the flux density was assumed to be 43.5 Jy at 1.4 GHz. The brightness temperature scale was calibrated against the IAU standard position S8, taken to have an integrated value of 897 $\pm 66$ K km s\textsuperscript{-1} (Williams 1973). The conversion between flux density in janskys per beam and brightness temperature in kelvin is 0.78 K (Jy beam\textsuperscript{-1}). The rms uncertainty in the observations is 0.15 Jy, equivalent to 0.12 K. Initial processing was carried out using the SLAP and SDCUBE software. Final data analysis was performed using the AIPS software package. All velocities used in this paper are referred to the LSR.

3. THE DISTANCE TO W28 AND THE SYSTEMIC VELOCITY

Previous distance estimates for W28 range between 1.3 and 3.6 kpc. Milne (1970) estimated the distance to W28 to be 1.3–1.5 kpc. Lozinskaya (1974) derived a distance of 3.6 kpc based on H\textalpha measurements (assuming an LSR velocity near +18 km s\textsuperscript{-1} for W28). Goudis (1976) estimated a distance of 1.8 kpc, Clark & Caswell (1976) suggested 2.3 kpc, a further estimate by Milne (1979) produced a distance of 2.4 kpc, and Venger et al. (1982) obtained a distance of 3 kpc based on H\textalpha absorption measurements carried out with the RATAN-600 telescope.

On the other hand, OH (1720 MHz) maser emission associated with W28 was detected by Frail et al. (1994) at LSR...
velocities between $+5$ and $+15$ km $s^{-1}$, with most of the OH lines having velocities between $+6$ and $+8$ km $s^{-1}$. Strong OH absorption lines at 1612, 1665, and 1667 MHz were reported at a radial velocity of $+7.3$ km $s^{-1}$ (Goss 1968), while various molecular species in the dense gas interacting with W28 have a central velocity around $+7$ km $s^{-1}$ (Pastchenko & Slysh 1974; Wootten 1981; Arikawa et al. 1999). Arikawa et al. (1999) have shown the existence of two different components in the CO emission at $+7$ km $s^{-1}$, a narrow line corresponding to unshocked, quiescent molecular gas and a broad line, most likely arising from gas overtaken by the SNR shock. An additional narrow CO component is detected at $+21$ km $s^{-1}$, but this line probably originates in an unrelated cloud along the line of sight. From these studies, we will adopt roughly $+7$ km $s^{-1}$ as the systemic velocity of W28. For this LSR velocity, circular rotation models provide near and far kinematic distances of 1.9 and 15 kpc. Because independent estimates favor the lower value, we adopt a distance of $1.9 \pm 0.3$ kpc for W28.

4. THE H I AROUND THE SNR W28

Figure 2 shows an H I profile obtained after averaging spectra from the entire observed region. The bottom panel depicts the Galactic rotation curve toward $l = 6^\circ.5$, $b = 0^\circ$ based on the model of Fich, Blitz, & Stark (1989), where $R_0 = 8.5$ kpc is assumed. The Galactic emission in this direction is mostly concentrated between $-50$ and $+50$ km $s^{-1}$, with a narrow absorption dip near $+7$ km $s^{-1}$. This is a very strong self-absorption feature produced by an unusually cold cloud that extends over a large region (covering at least $20^\circ$ of longitude in the direction of the Galactic center) and including the direction of W28 (Riegel & Jennings 1969).

Figures 3 and 4 show the distribution (in gray scale and white contours) of the H I emission within the velocity interval where significant H I emission is observed. In order to compare radio continuum and H I structures, the black contours represent the boundaries of the radio continuum emission associated with W28 (smoothed to the resolution of the H I data). The other bright continuum sources plotted in the field are the Trifid Nebula (M20; G07.00$-$0.3) to the left of W28 and the compact H II region W28 A-2 (G05.89$-$0.4) to the lower right corner of the figures. The average H I field emission has been subtracted from all the images for presentation purposes. The gray scale plotted along the upper edge of Figures 3 and 4 is kept constant in all images in order to emphasize changes in structures for different velocities. With the exception of the first image of Figure 3 and the two last images of Figure 4, where the integration intervals were chosen to be 35 and 30 km $s^{-1}$, respectively, the remaining images result from the average over 5 km $s^{-1}$ (six consecutive spectral channels). The central velocity of each integration interval is indicated in the top right corner of each panel.

The analysis of the H I distribution around W28 is quite complex, because of its location close to both the Galactic center and the Galactic plane. To identify structures that may be associated with the SNR, we look for features that may reveal the impact of the SNR expansion on the surrounding ISM (ring-shaped H I structures, expanding H II caps, etc.). In addition, we have attempted to locate H I concentrations that appear to be associated with prominent features observed in the radio continuum emission of W28.

Bright H I emission is observed at negative velocities. Based on Galactic circular rotation models, negative velocities should arise from gas at distances greater than 17 kpc. However, it is unlikely that the large bright structures observed between $V_{\text{LSR}} \approx -30$ and $-2$ km $s^{-1}$ correspond entirely to this distant gas. We have analyzed the H I features in this velocity range in an attempt to find associations with W28. The negative velocities could result from kinematic perturbations arising from the SNR.

Between roughly $-32$ and roughly $-2$ km $s^{-1}$ (Fig. 3), the brightest H I emission regions are preferentially distributed around W28, encircling the source along different sides. Particularly, at $V_{\text{LSR}} = -27.5$ km $s^{-1}$ and $V_{\text{LSR}} = -22.5$ km $s^{-1}$, H I concentrations can be observed, forming a clumpy incomplete shell. It is possible that part of this gas had been swept up by the expanding SN shock, although a “cap”-like feature would be the expected morphology for associated H I concentrations at these high negative velocities. Thus, the association is uncertain. At $V_{\text{LSR}} = -7.5$ and $-2.5$ km $s^{-1}$, a good coincidence is observed between H I concentrations and some distortions observed in the outer envelope of W28 along the eastern and northern sides. These structures are compatible with the hypothesis that the expanding shock wave of the SNR is pushing the interstellar neutral gas outward.

At $V_{\text{LSR}} = +2.5$ km $s^{-1}$, the H I surrounds W28 with an almost complete shell-like structure. A striking morphological correspondence is observed between the two H I maxima to the north and northeast of W28, at $(6^\circ50', +0^\circ15')$ and

![Figure 2](image-url)
The H\textsubscript{i} concentration near (6\degree50\arcmin, 0\degree20\arcmin) coincides with the CO concentration reported by Arikawa et al. (1999) to be quiescent molecular gas associated with W28. This H\textsubscript{i} component is also present in the following channel image at $V_{\text{LSR}} = +7.5$ km s\textsuperscript{-1} (Fig. 4, top left image). However, at $V_{\text{LSR}} = +7.5$ km s\textsuperscript{-1}, the H\textsubscript{i} feature in emission is masked by the strong absorption toward the SNR.

As mentioned before, in the image centered at $V_{\text{LSR}} = +7.5$ km s\textsuperscript{-1} (Fig. 4), the most remarkable feature is the central depression observed in H\textsubscript{i} emission. This H\textsubscript{i} depression results from self-absorption produced by an extended, cold cloud centered near +7 km s\textsuperscript{-1}, which is part of the complex of cold clouds reported by Riegel & Jennings (1969) in this direction of the Galaxy. To analyze the absorption features, in Figure 5 we display the negative contours (white lines) overlapping W28 (gray scale) as obtained from an integration of H\textsubscript{i} between +4 and +9 km s\textsuperscript{-1}. Based on Figure 5, we can conclude (1) that the cold cloud is much larger than the SNR, and (2) that the location of the deepest absorption hole does not coincide with the brightest synchrotron feature to the east of W28, but it approximately overlaps the thin radio filament that crosses W28 in the east-west direction (see Fig. 1). This synchrotron filament has been shown by Dubner et al. (2000) to have the flattest spectral index of all parts of the SNR. Associated with this filament, Arikawa et al. (1999) have shown the existence of shocked CO gas (with broad wings, between $V_{\text{LSR}} = -40$ and +40 km s\textsuperscript{-1}) and unshocked CO gas (between $V_{\text{LSR}} = +4$ and +9 km s\textsuperscript{-1}). The shocked CO is associated with numerous OH (1720 MHz) masers (Claussen et al. 1997, 1999). For the unshocked gas, Arikawa et al. (1999) estimate a kinetic temperature of $\leq$20 K, a density of $\leq 10^3$ cm\textsuperscript{-3}, and a total H\textsubscript{2} mass of 4000 $M_\odot$. For the shocked
gas, the physical parameters are as follows: a kinetic temperature of $\geq 20$ K, a density of $\geq 10^4$ cm$^{-3}$, and a total H$_2$ mass of 2000 M$_\odot$. We conclude that we have detected the atomic hydrogen counterpart of the unshocked molecular cloud associated with W28, thus confirming on the basis of H$\textsc{i}$ data the systemic velocity and the distance of 1.9 $\pm$ 0.3 kpc for W28. From the present data, we estimate that the mass of the cold H$\textsc{i}$ responsible for the self-absorption is 70 M$_\odot$. Therefore, only a small fraction of the total molecular gas mass is detected in atomic form.

At $V_{\text{LSR}} = +17.5$ km s$^{-1}$, a conspicuous H$\textsc{i}$ shell centered near ($l \sim 6^\circ 40', b \sim 0^\circ 12'$, with radius of $\sim 6'$) is observed surrounding the SNR. The presence of these concentrations distributed in a ringlike shape, together with the other features previously described at negative LSR velocities, suggest that part of the surrounding H$\textsc{i}$ gas may have been swept up by the expanding SNR shock wave, forming a thick H$\textsc{i}$ interstellar shell. The existence of diffuse thermal X-ray emission filling the interior of W28 (Rho & Petre 1996) supports the hypothesis that the center has been evacuated.

At higher positive velocities, the most noticeable feature that may be associated with W28 is the central concentration present at $V_{\text{LSR}} = +32.5$ and +37.5 km s$^{-1}$. This concentration appears to be projected onto the interior of the SNR and can be interpreted as the "cap" of the H$\textsc{i}$ shell expanding around W28.

Based on these results, we can propose a model in which the explosion took place near ($l, b, V$) = ($6^\circ 30', -0^\circ 12', +7$ km s$^{-1}$). The present shell radius is $\sim 0.6$, or 20 pc, at a distance of 1.9 kpc. On the basis of the adopted systemic velocity of +7 km s$^{-1}$ and the presence of a "cap"-like feature near +37 km s$^{-1}$, the expansion velocity of this structure is estimated to be about $30 \pm 3$ km s$^{-1}$.

The total associated H$\textsc{i}$ mass can be estimated by integrating the contributions of all the structures that are considered to be part of the atomic gas shell; in other words, the H$\textsc{i}$ emission between $V_{\text{LSR}} \sim -25$ km s$^{-1}$ and $\sim +37$ km s$^{-1}$, which appear encircling W28 in the different channel maps, plus the features projected onto the center of the SNR at the high positive velocities. After the subtraction of an appropriate background contribution (assumed to be 3 $\sigma$ below the isocontour that

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Fig. 4.—As in Fig. 3, H$\textsc{i}$ images in the velocity range [+7.5, +85] km s$^{-1}$. The last two images are obtained from integration over an interval of 30 km s$^{-1}$. No. 4, 2002 LARGE-SCALE HYDROGEN NEAR SNR W28 2149
outlines the associated features), an H\textsc{i} mass of 1600 \pm 240 \, M_\odot is obtained. The quoted error takes into account the uncertainties in the selection of the boundaries for the integration. This is an upper limit for the associated mass, since it is impossible to separate the contributions from unrelated H\textsc{i}. In this total mass estimate, about \sim 400 \, M_\odot correspond to the features at velocities more negative than -7.5 km s\textsuperscript{-1}, whose association with W28 may be questionable. Thus, the total swept up H\textsc{i} mass can vary between \sim 1200 and 1600 \, M_\odot.

Assuming that the mass is uniformly distributed over a sphere of radius of 20 pc, we obtain an upper limit for the ambient ISM density of \sim 1.5–2.0 cm\textsuperscript{-3} (depending on the value used for the total mass). The kinetic energy would be \E_{\text{kin}} \leq 1 \times 10^{49} \, \text{ergs} and the initial energy of the explosion about 1.4–1.8 \times 10^{50} \, \text{ergs} (based on Chevalier's 1974 model). Given these values for the initial explosion energy and the unperturbed ISM density and by considering the expression (Rohlfs & Wilson 1996)

$$\tau_{\text{rad}} = \left[ \frac{4.56 \times 10^7}{(1 + x_{\text{H}}) T_4} \left( \frac{E_{51}}{n_0} \right)^{2/5} \right]^{5/6} \, \text{yr}, \quad (1)$$

we can estimate the time for the onset of the radiative phase of SNR evolution to be \tau_{\text{rad}} \sim \sim 2.1–2.4 \times 10^4 \, \text{yr}, while \R_{\text{rad}} \sim 10 \, \text{pc} is the radius of the SNR at that stage. In equation (1), \T_4 is the temperature just behind the SNR shock wave (in units of 10\textsuperscript{4} K), which was set to 100 (radiative losses start to be an important process at about 10\textsuperscript{6} K), \E_{51} is the initial SN energy in units of 10\textsuperscript{51} ergs, \xH is the ionization fraction (assumed to be 0), and \n_0 is the unperturbed ISM density in cm\textsuperscript{-3}.

By assuming a radius of about 13 pc for W28 (from an angular size of \sim 23.5\textdegree and a distance of \sim 1.9 kpc), we can conclude that this remnant is well in the radiative phase of evolution and has a current age of 3.3 \times 10^4 \, \text{yr}, which is in

Fig. 5.—Overlay of the H\textsc{i} depression integrated between 4 and 9 km s\textsuperscript{-1} (white contours), as well as the W28 radio continuum (gray scale). The contours correspond to the \sim -26, -22, -18, -14, -10, -6, -2, and 2 Jy beam\textsuperscript{-1} km s\textsuperscript{-1} levels. The radio continuum of W28 (with a resolution of 88\textdegree \times 48\textdegree) is shown with a gray-scale range of [-0.06, 0.75] Jy beam\textsuperscript{-1}. 

![GALACTIC LAT. GALACTIC LONG.](image)
good agreement with previous age estimates (Friol, Kulkarni, & Vasishth 1993; Velázquez 1999). In this evolutionary stage, it is expected that a thin H i shell forms by recombination behind the shock front with a width of about 10% of the radius.

5. CONCLUSIONS

We have carried out a study of the neutral hydrogen in the environs of the SNR W28. Our analysis of the kinematics and distribution of the H i has revealed several H i features that are most probably associated with W28, revealing signatures of the interaction of this SNR with the ISM. We have detected, as a self-absorption feature around \( \sim 7 \) km s\(^{-1}\), the neutral gas counterpart of the molecular cloud detected by Arikawa et al. (1999) in unshocked CO gas. Based on the presence of this cold cloud, we can independently confirm a kinematical distance of 1.9 ± 0.3 kpc for W28.

Portions of an incomplete H i shell are also observed in emission at different positive and negative LSR velocities, with the maximum angular size (\( \sim 0.6\)) at \( V_{\text{LSR}} = \pm 17.5 \) km s\(^{-1}\). An H i cloud is detected near \( V_{\text{LSR}} = 37 \) km s\(^{-1}\), overlapping the center of W28. We interpret this last feature as the “cap” of the irregular expanding interstellar shell swept up by the W28 shock front. The mass of this shell has been estimated to be between 1200 and 1600 \( M_\odot \).

Based on the present results, the following scenario for W28 can be proposed:

1. A SN explosion of energy \( \sim 1.6 \times 10^{50} \) ergs occurred about \( 3.3 \times 10^4 \) yr ago at the position \((l, b) = (6^h 30', 0^\circ 12')\) and at distance of \( \sim 1.9 \) kpc. At this location, the ambient density of the ISM was \( \sim 1.5 - 2 \) cm\(^{-3}\).

2. The expanding shock wave has collided with a cold gas concentration, observed as an absorption H i feature and as molecular clouds around the LSR velocity of 7 km s\(^{-1}\). The mass of this cold cloud (\( \sim 70 \) \( M_\odot \)) is only a small fraction of the total mass estimated for molecular hydrogen. Most of the atomic hydrogen is detected in emission as an H i shell, as mentioned below.

3. The interaction of the SN shock front with the surrounding H i gas has swept up a thick interstellar H i shell, currently expanding at \( \sim 30 \) km s\(^{-1}\). W28 has entered into the radiative stage of evolution about \( 10^4 \) yr ago. However, the thin neutral shell expected to form by recombination behind the shock front could not be identified because of the relatively low angular resolution of the present study.

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