The Distance to SS 433/W50 and its Interaction with the Interstellar Medium

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to appear in MNRAS

ABSTRACT

The distance to the relativistic jet source SS 433 and the related supernova remnant W50 is re-examined using new observations of H I in absorption from the VLA, H I in emission from the GBT, and 12CO emission from the FCRAO. The new measurements show H I in absorption against SS 433 to a velocity of 75 km s\(^{-1}\) but not to the velocity of the tangent point, which bounds the kinematic distance at 5.5 \(\leq d_k < 6.5\) kpc. This is entirely consistent with a 5.5 \(\pm 0.2\) kpc distance determined from light travel-time arguments (Blundell & Bowler 2004). The H I emission map shows evidence of interaction of the lobes of W50 with the interstellar medium near the adopted systemic velocity of \(V_{\text{LSR}} = 75\) km s\(^{-1}\). The western lobe sits in a cavity in the H I emission near the Galactic plane, while the eastern lobe terminates at an expanding H I shell. The expanding shell has a radius of 40 pc, contains \(8 \pm 3 \times 10^3\) M\(_\odot\) of H I and has a measured kinetic energy of \(3 \pm 1.5 \times 10^{49}\) ergs. There may also be a static H I ring or shell around the main part of W50 itself at an LSR velocity of 75 km s\(^{-1}\), with a radius of 70 pc and a mass in H I of \(3.5 - 10 \times 10^4\) M\(_\odot\). We do not find convincing evidence for the interaction of the system with any molecular cloud or with H I at other velocities. The H I emission data suggest that SS 433 lies in an interstellar environment substantially denser than average for its distance from the Galactic plane.

This Population I system, now about 200 pc below the Galactic plane, most likely originated as a runaway O-star binary ejected from a young cluster in the plane. Given a modest ejection velocity of \(\geq 30\) km s\(^{-1}\), the binary could have reached its present location in \(\leq 10\) Myr at which time the more massive member became a supernova. New astrometric data on SS 433 show that the system now has a peculiar velocity of a few tens of km s\(^{-1}\) in the direction of the Galactic plane. From this peculiar velocity and the symmetry of the W50 remnant we derive a time since the SN of \(\leq 1 \times 10^5\) yr.

Key words: ISM: H I — SNR: individual (W50) — ISM: jets and outflows — stars: individual (SS 433) — supernova remnants

1 INTRODUCTION

From its discovery as an eclipsing X-ray binary star emitting relativistic jets, the distance to SS 433 and the W50 supernova remnant (SNR) in which it is embedded has been somewhat uncertain. The peculiar and exciting properties of this system were first described by Margon et al. (1979), who estimated its kinematic distance as 3.5 kpc from observations of the velocity of highly saturated foreground interstellar NaII lines and a straightforward model for Galactic rotation. As the properties of SS 433 became better understood — it is a compact object in a binary system ejecting relativistic jets along an axis which precesses through small angles — the determination of its distance became more important in fixing the physical size of the observed phenomena. From a measurement of the proper motion of individual radio structures within the SS 433 jets, and the assumption of a constant jet velocity, Hjellming & Johnston (1981a); Hjellming & Johnston (1981b) derived a distance of 5.5\(\pm 1.1\) kpc, which was soon adopted as the canonical value for the system (Margon 1984).

Figure shows SS 433 and W50 in relation to the Galac-
Figure 1. The 11cm continuum image made at 4′3″ angular resolution (Reich et al. 1990) of the region containing W50, which is centred on SS 433. The SS 433 jets are shown schematically at the approximate correct orientation and scale. The H II region S74 and the extragalactic radio source B1910+052, which is superimposed on the W50 shell, are also noted.

SS 433 is located at ℓ, b = 39°7′−2°2′, in the centre of the radio continuum source W50, which is thought to be either a supernova remnant or a stellar wind bubble (Königl 1983). The SS 433 system consists of a compact object surrounded by an accretion disc and a ‘donor’ star, of M ≳ 10M⊙ (Hillwig et al. 2004). Material from the donor star passes to an accretion disc surrounding the compact object and generates two relativistic jets moving at 0.26c in opposite directions which have apparently created the lobes (or ‘ears’) punched through the rim of the circular SNR W50 (Begelman et al. 1980; Margon 1984). The jet axis precesses with a cone opening angle of 20° around a position angle of 98° (Margon 1984; Stirling et al. 2002), though at their maximum extent they show evidence of having been collimated to an effective opening angle ∼ 10° (Brinkmann et al. 2006). The jet closer to the Galactic plane is usually referred to as the ‘Western’ jet and the other as the ‘Eastern’. The presence of a ∼ 10M⊙ (hence young) star in SS 433 clearly marks this system as part of Population I, a classification whose implications we will discuss in §7.

The stellar component of SS 433 cannot be assigned a distance from traditional spectro-photometric or kinematic techniques: the nature of the donor star is still uncertain (Fuchs et al. 2006), as is the extinction, while the optical systemic radial velocity of +82 ± 3 km s−1 (V_LSR) may have a significant random component acquired during the supernova (SN) (Hillwig et al. 2004). But as a radio source, SS 433 can be used as a target for HI absorption measurements: the kinematics of the intervening gas seen in absorption can provide limits on the location of SS 433, limits which are not likely to be affected by conditions close to the source itself (Murdin, Clark, & Martin 1980). Such measurements were first made by van Gorkom, Goss, & Shaver (1979) and showed that SS 433, and by implication the entire W50 remnant, absorbed HI only at a V_LSR < 53 km s−1, which limits the kinematic distance to d_k ≥ 3.7 kpc. The authors noted that their measurements might be consistent with a kinematic distance of as much as 4.7 kpc, but this rather uncertain upper limit was rendered less probable by subsequent observations of HI absorption toward the extragalactic radio continuum source B1910+052 only 25″ from SS 433 (Fig. 1), which has a rich absorption spectrum at all velocities up to the maximum allowed from Galactic rotation (Dickey et al. 1983). This implies that if SS 433 were actually 5 kpc from the Sun, HI should be seen in absorption against it to at least 75 km s−1, more than 20 km s−1 higher than was detected. (Throughout this paper velocities are given with respect to the LSR defined from “Standard Solar Motion” (Delhaye 1965) unless otherwise noted.)

Observations of 12CO from molecular gas added to the puzzle. SS 433/W50 lies more than 2 degrees from the Galac-
tic plane, an uncommonly large latitude for Population I objects in the inner Galaxy except for those quite near to the Sun. Observations of $^{12}$CO showed that there is a large molecular cloud covering SS 433 with a velocity in the range 27–36 km s$^{-1}$ and an implied distance of 2.2 kpc (Huang, Dame & Thaddeus 1983, Yamamoto et al. 1999), though the ‘far’ kinematic distance of ~ 11 kpc might also be possible. The $^{12}$CO data did not show strong kinematic or morphological evidence for an interaction between W50 and the molecular cloud, but the coincidence of an SNR and molecular cloud $\approx 2^\circ$ from the Galactic plane was thought to make their association likely. Furthermore, the HII region S74 lies projected on the edge of the W50 remnant (Fig. 1), between the remnant and the Galactic plane. S74 is associated with $^{12}$CO emission at 48 km s$^{-1}$ and the spectro-photometric distance to its exciting star is relatively bright, so stray radiation from GBT sidelobes are processed for 4$^\circ$. The data were gridded to a final resolution of 3$^\prime\!\!\!\prime$ at a position angle of 54$^\circ$ at a position angle of 76$^\circ$ for this epoch. The continuum peak at this resolution is 750 mJy/beam. The rms noise in H I opacity channel is about 0.004 for both sets of observation.

2 OBSERVATIONS

2.1 VLA H I Absorption Measurements

The Very Large Array (VLA) of the NRAO was used to observe SS 433 during two periods of about 40 minutes each on 5 June 1998 when it was being moved from A to B configuration. The nearby 1.2-Jy object J1950+081 was used as a phase calibration source. The bandpass and total flux density scale were calibrated by observations of 3C48. The first observations were made with a velocity coverage of 160 km s$^{-1}$ at a resolution of 1.29 km s$^{-1}$ over 127 channels. The synthesized beam was 27$^\prime\!\!\!\prime$ × 17$^\prime\!\!\!\prime$ at a position angle of 90$^\circ$. The rms noise per channel is 3.5 mJy/beam while the continuum peak is 612 mJy/beam. During the second set of independent observations the bandwidth was twice as large, giving a velocity resolution of 2.58 km s$^{-1}$, an rms noise of 3.0 mJy/beam, and angular resolution of 3$^\prime\!\!\!\prime$ × 1$^\prime\!\!\!\prime$.9 at a position angle of 76$^\circ$ for this epoch. The continuum peak at this resolution is 750 mJy/beam. The rms noise in H I opacity channel is about 0.004 for both sets of observation.

2.2 GBT H I Emission Measurements

An image in the 21-cm emission line of H I was constructed for the region around SS 433 using archival data from the Robert C. Byrd Green Bank Telescope (GBT) as well as observations made specifically for this project with the GBT. In all cases the spectra cover about 500 km s$^{-1}$ in total, centred at ±50 km s$^{-1}$ with a channel spacing of 1.03 km s$^{-1}$ and an effective velocity resolution of 1.25 km s$^{-1}$. The region around W50 was mapped by making a series of scans in Galactic longitude at a fixed latitude. Spectra were measured every 3$^\prime$ in both coordinates. Each position was observed for 4$^\circ$. The data were gridded to a final resolution of 3$^\prime\!\!\!\prime$, slightly finer than Nyquist sampling for the 9$^\prime\!\!\!\prime$ angular resolution of the GBT. The ‘on-the-fly’ observing and subsequent gridding gave the final maps an effective angular resolution of 10$^\prime\!\!\!\prime$ × 9$^\prime\!\!\!\prime$ in Galactic longitude and latitude, respectively. A 2nd order polynomial was fitted to emission-free regions of the spectra, and the rms noise in the final spectra is 0.10 K.

The H I emission associated with SS 433 is relatively bright, so stray radiation from GBT sidelobes should not be an issue here. There was, however, a small error in the velocity tracking while observing some portions of the mapped region, which resulted in an ~ 0.1 km s$^{-1}$ error in the velocity scale of many spectra. This is $\leq$10% of a velocity channel width, but it can vary systematically from row to row, and can be seen as a faint striping when there are strong gradients in $T_b(V)$. For quantitative purposes this problem is negligible, but it does occur in some of the images.

2.3 FCRAO $^{12}$CO Emission Map

The $^{12}$CO data were obtained for us by C. M. Brunt and M. H. Heyer using the 14 m telescope of the Five College Radio Astronomy Observatory (FCRAO) with the SEQUOIA 32 pixel focal plane array. An area about 2$^\circ$ × 2$^\circ$ centred on SS 433 was fully sampled at an angular resolution of 45$^\prime\!\!\!\prime$, and the data were gridded into a cube with a pixel size of 3.0 mJy/beam. The synthesized beam was 27$^\prime\!\!\!\prime$ × 17$^\prime\!\!\!\prime$ at a position angle of 90$^\circ$. The rms noise per channel is 3.5 mJy/beam while the continuum peak is 612 mJy/beam. During the second set of independent observations the bandwidth was twice as large, giving a velocity resolution of 2.58 km s$^{-1}$, an rms noise of 3.0 mJy/beam, and angular resolution of 3$^\prime\!\!\!\prime$ × 1$^\prime\!\!\!\prime$.9 at a position angle of 76$^\circ$ for this epoch. The continuum peak at this resolution is 750 mJy/beam. The rms noise in H I opacity channel is about 0.004 for both sets of observation.
of 20". Spectra cover 65 km s$^{-1}$ from 7.5 to 72.5 km s$^{-1}$ at a velocity resolution of 0.063 km s$^{-1}$, though for this paper we smoothed the spectra to a velocity resolution of 0.25 km s$^{-1}$. The rms noise in the spectra is about 0.4 K. Further information on the FCRAO 14-m system is given in Heyer, Williams, & Brunt (2006).

3 HI ABSORPTION AND THE KINEMATIC DISTANCE OF SS 433

Figure 2 shows the expected run of $V_{LSR}$ with distance from the Sun, $d$, in the direction of SS 433 for a flat rotation curve with $R_0 = 8.5$ kpc and $V_0 = 220$ km s$^{-1}$. Other models for Galactic rotation in the inner Galaxy (e.g., Burton (1992); Clemens (1983)) differ from a flat curve by only a few km s$^{-1}$ at the distances shown in the Figure. For an azimuthally symmetric rotation curve, $V_{LSR}$ is symmetric about the tangent point distance, $d_t = R_0 \cos(\ell)$, then becomes negative at $d > 13$ kpc, where $R > R_0$. The value of $V_{LSR}$ at the tangent point, $V_t$, for the flat rotation curve model is within a few km s$^{-1}$ of measured values of $V_t$ for $^{12}$CO in the Galactic plane at similar longitudes (Clemens 1983) and also agrees with the maximum velocity of H I absorption toward the extragalactic radio source B1910+052, which lies projected on the rim of W50 (Dickey et al. 1983).

The line of sight to SS 433 at $\ell \approx 40^\circ$ lies beyond the region of the Galaxy influenced by strong streaming motions around the Galactic bar (e.g., Weiner & Sellwood (1994)), but large-scale density wave motions may still be important (e.g., Englmaier & Gerhard (2006); Brand & Blitz (1993)) have tried to determine the true velocity field of the Galaxy using distances to the exciting stars of HII regions and velocities from $^{12}$CO measurements of the associated molecular clouds. Their results in the direction of SS 433 are shown by starred symbols in Fig. 2. The H I region S74 (which is projected on the edge of W50) is shown as an open square, with the 20% distance uncertainty estimated by Forbes (1985). The S74 distance is based on measurement of a single star and may have an error larger than 20%. S74 itself has significant weight in the determination of the Brand & Blitz velocity field in this direction, but there are a few other HII regions whose distance and kinematics also imply that the Galactic velocity field rises somewhat steeply for a few kpc from the Sun before returning to the "flat" value at $d = 3$ kpc (Brand & Blitz 1993).

The arrow marked "SS 433 vanG 79" shows the maximum velocity of H I absorption toward SS 433 found by van Gorkom, Goss, & Shaver (1979). While this gives $d_t \geq 3.7$ kpc for a flat rotation curve, the Brand & Blitz (1993) empirical velocity field suggests that the limit might be even more stringent: $d_t \geq 2$ kpc. The arrow labelled 'B1910+052' marks the velocity limit of H I absorption toward the radio continuum source B1910+052 only 25′ away from SS 433 (Dickey et al. 1983). This source has an H I absorption component at -20 km s$^{-1}$ showing that it is > 10 kpc from the Galactic Centre and thus almost certainly extragalactic. At positive velocities it has H I in absorption continuously between 0 and 80 km s$^{-1}$ and supplies us with two important facts: cool H I is most likely present at all permitted velocities along the line of sight to SS 433, and the value of $V_t$ given by the flat rotation curve is correct to within a few km s$^{-1}$.

Figure 3 shows the spectrum of H I in absorption against SS 433 (lower panel) obtained from the new high-velocity resolution VLA observations and the corresponding emission spectrum from the GBT observations (upper panel). The independent VLA absorption spectrum made with lower velocity resolution is consistent with the data shown here. H I absorption components are detected at $V_{LSR} = 75$ km s$^{-1}$, a kinematic distance of $d_k \geq 5.5$ kpc, as indicated by the arrow in Fig. 2. The relatively weak $\tau_{HI} = 0.05$ absorption at $V_{LSR} = 75$ km s$^{-1}$ was not detected in previous data, though hints of it at the 3σ level can be seen in the data of Dickey et al. (1983). In the new VLA spectra it is significant at a level > 10σ above the noise.

Figure 4 shows the high-velocity portion of the VLA H I absorption spectrum toward SS 433 (this paper) and toward B1910+05, the extragalactic source only 25′ from SS 433 (Dickey et al. 1983). The absence of H I absorption toward SS 433 at velocities $\geq 80$ km s$^{-1}$, which is the terminal velocity where absorption is seen toward B1910+05, implies that SS 433 is nearer than the tangent point distance $d_t = R_0 \cos(\ell)$ = 6.5 km s$^{-1}$. Thus the H I absorption data taken in total give 5.5 $\leq d_k < 6.5$ kpc.

These values are consistent with the distance derived from a light-travel time analysis and we therefore adopt the distance of $d = 5.5 \pm 0.2$ kpc, and take $V_{LSR} = +75 \pm 6$ km s$^{-1}$ as the systemic velocity of the the equivalent standard of rest of the SS 433/W50.
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Figure 3. The upper panel shows the GBT 21cm H I emission spectrum towards SS 433 and the lower panel shows the high-velocity resolution VLA absorption spectrum plotted as $\tau(V_{\text{LSR}})$. Significant H I absorption at 75 km s$^{-1}$ is seen for the first time and establishes the kinematic distance of SS 433 as $\geq 5.5$ kpc.

system, where the uncertainty is the typical random motion of cool H I clouds (Dickey & Lockman 1990). This velocity is close to the mean velocity of the SS 433 binary system (Hillwig et al. 2004), which, however, may have a significant peculiar velocity acquired during the SN event. This is discussed more fully in §7.

4 SS 433 AND THE MOLECULAR CLOUD AT 30 KM S$^{-1}$

In this section we examine the evidence that SS 433 is interacting with a molecular cloud at a velocity of about 30 km s$^{-1}$, as has been suggested by some previous work (Huang, Dame & Thaddeus 1983; Yamamoto et al. 1999).

Figure 5 shows a $^{12}$CO spectrum towards SS 433 derived from the new observations with the FCRAO, while Figure 6 shows the $^{12}$CO emission integrated over the velocity range 22–38 km s$^{-1}$. The image includes $^{12}$CO at all velocities which were considered to be connected with W50 in the earlier studies (Huang, Dame & Thaddeus 1983; Yamamoto et al. 1999), which is virtually all of the $^{12}$CO in this part of the sky. The right panel of Fig. 6 shows the integrated $^{12}$CO intensities overlaid with contours of the 1.4 GHz continuum of W50 from Dubner et al. (1998). There is no obvious relationship between the $^{12}$CO emission and the radio continuum, and, except that they both lie somewhat below the Galactic plane, nothing in these data suggests any connection. Scrutiny of line velocity and line width maps leads to a similar conclusion.

The FCRAO $^{12}$CO data also show that the S74 HII region (Fig. 1) is not connected with either the SS 433/W50 system, or with the molecular cloud at 22–38 km s$^{-1}$. $^{12}$CO emission associated with S74 is seen only between 40 and 47 km s$^{-1}$, and only in the immediate vicinity of the nebula. There is no $^{12}$CO at the velocity of S74 within the boundaries of W50, so the HII region S74 seems also to be a chance overlap on the sky with the edge of the remnant. The highest velocity $^{12}$CO emission in this field comes at 56 km s$^{-1}$ from a small cloud at $\ell, b = 30^{\circ}.6 - 1^{\circ}.6$, just touching the top of the western lobe. Both the FCRAO and the lower-resolution $^{12}$CO data (Huang, Dame & Thaddeus 1983; Dame et al. 2001) have no significant $^{12}$CO emission at velocities $> 56$ km s$^{-1}$ except for general emission from the molecular cloud layer near the Galactic plane at $b \geq -1^\circ$.

Thus we find no evidence for a molecular cloud near the lon-
5 THE INTERACTION BETWEEN SS 433/W50 AND INTERSTELLAR H I

5.1 The Western Jet: A Cavity in H I

The Western lobe of SS 433 terminates at $b \approx -1.5^\circ$ where the W50 radio continuum contours sit in a slight cavity in the H I, seen most clearly at $V_{LSR} > 75$ km s$^{-1}$, e.g., at the 83 km s$^{-1}$ emission shown in Figure 7. It is likely that the interaction is more visible at the higher velocities simply because there is less confusion from unrelated emission.

5.2 The Eastern Jet: An Expanding H I Shell

The eastern lobe of the continuum source terminates abruptly at the edge of a well-defined expanding shell of H I, shown at several velocities in Figure 8. The shell is at its maximum angular extent at the velocities of the top two panels of the Figure, and at its greatest velocity in the lower left panel, where it has contracted to a single receding ‘cap’. The expanding shell is open to the South, perpendicular to the axis of the jet, and may also have a gap where it overlaps the continuum lobe itself. The solid red line in the Figure lies along the extension of the axis of the SS 433 jets. At 82 km s$^{-1}$ the axis of the jet intersects a chevron of H I which lies along the extension of the axis of the jet itself. The solid red line in the Figure lies along the extension of the axis of the SS 433 jets. At 82 km s$^{-1}$ the axis of the jet intersects a chevron of H I which points in the direction of the jet motion (lower right panel). This feature is also visible in Fig. 7.

The expansion of the shell is demonstrated in Figure 9 through velocity-longitude and velocity-latitude cuts along the direction of the dashed lines marked in Fig. 8. The centre of kinematic symmetry of the shell is at $40^\circ - 2^\circ 3^\prime 9$ at $V_{LSR} \approx 71$ km s$^{-1}$, and its expansion velocity is $V_e = \pm 16$ km s$^{-1}$. Figure 10 shows a GBT H I spectrum at $40^\circ - 2^\circ 3^\prime 8^\circ$, the position marked by the yellow star in Fig. 8. This particular spectrum was chosen for display because it shows the major components of the system most distinctly. The receding part of the shell (marked ‘R’) is well-separated in velocity from other H I emission and reaches $V_{LSR} \approx 85$ km s$^{-1}$, well beyond the terminal velocity in its direction (Fig. 2). The approaching side of the shell, labelled A, is a distinct component in the spectra, though it cannot be measured accurately at most locations. In this direction the receding component has $N_{HI} = 4.9 \times 10^{19}$ cm$^{-2}$ and a line width $\Delta V = 6$ km s$^{-1}$ (FWHM), values typical of directions through the centre of the shell, which have a range in $N_{HI}$ of $3.9 \times 10^{19}$ cm$^{-2}$ and
in $\Delta V$ of 4–10 km s$^{-1}$. In many places the shell appears to be barely resolved by the GBT beam: it must have an intrinsic thickness (FWHM) $\lesssim$12$\arcmin$, or $\lesssim$20 pc at the distance of SS 433.

5.2.1 Mass, density, and energetics

At an adopted distance of 5.5 kpc, a simulated shell with a Gaussian radial density profile, a radius to the peak of 40 pc and a thickness (FWHM) of 20 pc fit the data reasonably well. Assuming that the gap in the shell covers 10% of its surface area, the total H I mass is $8 \times 10^3 M_\odot$. For the expansion velocity of $\pm 16$ km s$^{-1}$, and a mean particle mass of $1.4 m_H$, the total measured kinetic energy in the shell is $E_k = 3 \times 10^{49}$ ergs. The H I mass divided by the volume of the sphere to its outermost radius gives the initial density $n_0 = 0.4$–1.2 cm$^{-3}$, a range which covers all plausible values of its size. This is about an order of magnitude larger than the interstellar densities expected this far from the plane (Dickey & Lockman 1990). The properties of the expanding
Figure 9. GBT HI data in velocity-longitude and velocity-latitude cuts at $\ell = 40^{\circ}22$ and $b = -3^{\circ}73$ showing the expanding shell at $\ell, b, V_{\text{LSR}} = 40^{\circ}5, -3^{\circ}9, +71$ km s$^{-1}$. This structure extends over $39^{\circ}6 < \ell < 40^{\circ}8$ and $-3^{\circ}0 < b < -3^{\circ}4$, has an expansion velocity of $\pm 16$ km s$^{-1}$, and touches the tip of the lower W50 lobe. The letter ‘R’ identifies the receding part of the shell, and ‘N’ a negative-velocity HI feature which might be associated with it.

Figure 10. The GBT HI spectrum through the expanding shell at $40^{\circ}0-3^{\circ}9$, the position marked by a star in the panels of Fig. 8. Spectral components associated with the receding and approaching side of the bubble are indicated with ‘R’ and ‘A’. There is a possible negative velocity component ‘N’ which will be discussed in a later section.

shell are summarised in Table 1, where the errors attached to each quantity include the range of measurement uncertainty and the effect of a $\pm 1$ kpc change in the adopted distance.

5.3 A static ring or shell around W50

The HI emission at the adopted systemic velocity of 75 km s$^{-1}$, as measured with the GBT along a path at constant declination, approximately parallel to the long axis of the SS 433 system, is shown in Figure 11. This track cuts through four distinct ridges of HI which are superimposed upon a strong gradient. The two ridges at higher Right Ascension belong to the expanding shell discussed in the previous section. The two ridges at lower Right Ascension appear to be the edges of a static HI ring or shell.

The GBT image of HI emission at 74 km s$^{-1}$ is shown in Figure 12. In the right panel the temperatures have been scaled by $\sin |b|$ to flatten somewhat the very strong HI brightness gradient near the Galactic plane and accentuate HI features which have a significant deviation from a smooth layer. The two western ridges in Fig. 11 come from cuts through an irregular ring of emission centred at $\ell, b = 39^{\circ}6 - 1^{\circ}8$ on the upper part of the W50 remnant. It is possible that the HI cavity illustrated in Fig. 7 is part of this ring.

Figure 11. The HI brightness temperature at $V_{\text{LSR}} = 75$ km s$^{-1}$ from GBT data along a cut at $\delta = 04^{\circ}25'$, approximately parallel to the jets of SS 433 but $35'$ south of SS 433 itself. This slice shows four HI ridges possibly associated with SS 443/W50. S1 and S2 are cuts through the expanding shell (Fig. 8). R1 and R2 are part of what appears to be an HI ring or static shell which surrounds the western part of W50. The strong HI brightness gradient to lower Right Ascension results from the change in Galactic latitude from $-5^{\circ}$ to $-1^{\circ}$ over this range.

The HI ring appears to be slightly elliptical with an average diameter $\approx 135$ pc (for a distance of 5.5 kpc) and a thickness in places of about 40 pc. Figure 13 shows the HI spectrum at $39^{\circ}15 - 2^{\circ}50$ through the lower part of the
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Figure 12. The GBT 21cm H I emission in a 2 km s\(^{-1}\) velocity range around 74 km s\(^{-1}\) showing the static H I ring surrounding the upper part of the W50 system. The image on the left shows H I brightness temperature while the image on the right has temperatures scaled by \(\sin|b|\) to increase the dynamic range and accentuate deviations from a plane-parallel H I layer. The outline of the 1.4 GHz radio continuum from W50 [Dubner et al. 1998] is in red; SS 433 is at the central red contour. The location of the 1-dimensional cut of Figure 11 is shown by the dashed red line.

Figure 13. The GBT 21cm H I emission spectrum toward a position on the lower part of the static H I ring around W50. The ring component is the highest velocity peak in the spectrum, marked with the arrow.

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5.3.1 Mass and Density

The uncertain topology causes a considerable uncertainty in the derived mass because of the need to disentangle the object from unrelated emission. The visible ring contains \(\sim 3.5 \times 10^4\) \(M_\odot\) of H I, assuming the centre of the ring is at the background level. It can also be modelled as a complete shell, however, whose ring-like appearance results mainly from limb-brightening. In this case the data can be matched by a shell with a Gaussian radial density profile with a peak H I volume density \(n_{HI} = 1.2\) cm\(^{-3}\) at a radius of 80 pc, a FWHM of 40 pc, and a total mass in H I of \(10^5\) \(M_\odot\). The average interstellar density is given by the mass divided by the volume, which, because the volume of this object depends on its assumed shape, is not well constrained. Over the range of plausible assumptions we find \(n_0 \approx 1 - 2\) cm\(^{-3}\), at least an order of magnitude greater than the average H I density expected this far from the Galactic plane [Dickey & Lockman 1990], a relative excess similar to that found around the expanding shell.

6 HI EMISSION TOWARD SS 433/W50 AT OTHER VELOCITIES

We searched for a possible association between W50 and H I emission at all other velocities and present the results here. Although there are some coincidences, we do not believe that they are significant.

6.1 +40 km s\(^{-1}\)

Dubner et al. (1998) detected a void in the H I surrounding W50 at a velocity near 40 km s\(^{-1}\) in maps made at 21\arcmin res-
not look like a swept-up wall, but extends off our image to higher longitude and more negative latitude. It seems to be a large HI cloud and not part of a shell. On consideration of energetics and morphology we find it implausible that the 40 km s$^{-1}$ feature is associated with SS 433/W50.

The least gratifying but most likely circumstance given all the evidence is that the apparent connection at this velocity is coincidental overlap along our line of sight of an unrelated HI feature. Whereas the expanding shell and ring discussed in the previous section have both a spatial and kinematic correspondence with the SS 433/W50 system, the void at 40 km s$^{-1}$ matches only in its general shape. We conclude that it is unlikely that the apparent HI void at 40 km s$^{-1}$ is related to SS 433.

6.2 High positive-velocity HI

Koo & Heiles (1991) reported the possible detection, though at low statistical significance, of very weak high-positive-velocity HI in measurements made with an angular resolution of 35$^\prime$ in the direction of W50. In the Dubner et al. (1998) model this was assumed to be material accelerated by W50. The GBT data show no evidence for an excess of H I toward W50 at velocities $V_{LSR} \gtrsim 120$ km s$^{-1}$ to a level of $N_{HI} \approx 0.6 \pm 2.0 \times 10^{10}$ cm$^{-2}$ (1 $\sigma$), and thus we find no evidence of a high-velocity receding neutral shell around W50.

6.3 HI at -35 km s$^{-1}$

Dubner et al. (1998) suggested that a ridge of HI in their data near -35 km s$^{-1}$ might be material accelerated by the shock front associated with the near-side expansion of W50. There was also some evidence from earlier H I observations of a shell around W50 at this velocity (Gosachinskii & Khersonskii 1987). The GBT image is shown in Figure 15 with $T_d$ scaled by $\sin |b|$ to reduce the strong latitude gradient. We can find no concentration of HI that has a clear association with W50 in this velocity range.

6.4 A possible component of the expanding shell at -14 km s$^{-1}$

Fig. 16 shows the image of the HI emission feature labelled ‘N’ in Figs. 9 and 10. We are doubtful of any association with the expanding shell simply because its velocity of -14 km s$^{-1}$ is so extremely different from that of the rest of the shell. Nonetheless, it is relatively compact and is projected on the centre of the expanding shell, so we consider the consequences of its association. This component has a peak $N_{HI} = 8 \times 10^{19}$ cm$^{-2}$ with a linewidth $\Delta v = 5$ km s$^{-1}$. The position of its peak is 30°34’-3°88 and it extends 30’ in longitude at $< 10'$ in latitude for a size $(50 \times 16) d_{65.5}$ pc, where $d_{65.5}$ is the distance in units of 5.5 kpc. Its HI mass is $1.2 \pm 0.3 \times 10^3 d_{65.5}^2 M_\odot$, and if it has been ejected from the expanding shell, its kinetic energy would be $E_k \approx 0.9 \pm 0.2 \times 10^{50} d_{65.5}^2$ ergs.

We will not discuss this cloud any further as we consider it unlikely to be associated with the expanding shell, whose systemic velocity is $71 \pm 3$ km s$^{-1}$ and which seems to be a
The Distance to SS 433/W50 and its Interaction with the ISM

7 THE ORIGIN OF SS 433: A RUNAWAY BINARY FROM THE PLANE

Most studies of the SS 433 system conclude that it is comprised of a compact object (possibly a black hole) which likely began its life as an O star, and a ‘donor’ star of mass $\gtrsim 10 M_\odot$ (e.g., Hillwig et al. 2004; Fuchs et al. 2006). By these standards, the system must be relatively young and belong to Galactic Population I. It is located, however, quite far from the Galactic plane. The young, massive stars in the inner Galaxy traced by HII regions have a vertical distribution with a dispersion $\sigma_z = 20$ pc, consistent with the scale height of OB stars in the solar neighbourhood (Lockman, Pisano, & Howard 1996; Reed 2000; Maiz-Apellániz 2001). At a distance from the Galactic plane $z = -215$ pc, the location of SS 433 is certainly unusual, and as a massive binary it would have attracted notice even if it had not become an extraordinary system. Its isolation is illustrated in Figure 17 which shows the radio continuum with respect to molecular clouds and HII regions in its area of the Galaxy. As noted in §4, there is no trace of a molecular cloud at its longitude, latitude and velocity. It is thus highly likely that it was formed near the plane and not at its present location, and must have acquired a peculiar vertical velocity $\gtrsim 30$ km s$^{-1}$ to reach $z = -215$ pc.

Most, if not all, early-type stars found far from the Galactic plane are runaways which have been ejected from their parent cluster (Blaauw 1961; Gies 1987). Some have a proper motion which allows them to be traced back to their origin (e.g., Hoogerwerf et al. 2001). Binary stars can also be ejected from young clusters. The frequency of binaries among early-type runaway stars is small, but not zero (Mason et al. 1998; Martin 2006; McSwain et al. 2007), and theoretical studies suggest that binaries containing massive stars can be ejected from clusters at velocities $\lesssim 50$ km s$^{-1}$; the more massive the system ejected, the lower the ejection velocity (Leonard & Duncan 1990). At the location in the Galaxy of SS 433, an object launched from $z = 0$ with a vertical velocity $\approx 30$ km s$^{-1}$ in the Galactic potential given by Wolfire et al. (1995) will reach the altitude of SS 433 in about 8 Myr. As importantly, because of the long turnaround time, it will stay at $z \approx -200$ pc for between 8 and 18 Myr after leaving the plane. This corresponds to the main sequence lifetime of stars with $M \approx 20 - 25 M_\odot$ (Hirschi et al. 2004). It is thus reasonable that SS 433 began in one of the young clusters in the Galactic plane, was given a random kick of a few tens of km s$^{-1}$ (comparable to the velocity dispersion of the population of runaway OB stars (Stone 1991)), and made its way as an OB binary to $z \approx -200$ pc where the more massive star became a SN forming W50 and SS 433.

The other possibility is that the supernova occurred while the binary was still in the Galactic plane and the SN caused its own ejection (Iben & Tutukov 1997), now with a compact object as one member of the system (van den Heuvel et al. 1980). Arguments for this scenario are summarised by Königl (1983), who notes that it would find support if SS 433 has a peculiar velocity directed away from the Galactic plane.

Recent astrometric studies of SS 433 using the VLBA have been made at three epochs (A. Mioduszewski and M. Rupen, private communication) and a proper motion has

very regular structure with a uniform expansion velocity of 16 km s$^{-1}$.

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been detected. Those results will be described in full elsewhere; here we use them in the discussion of the origin of SS 433 and its interaction with the ISM. The Mioduszewski and Rupen measurements in March 1998 and August 2005 combine to give a proper motion $\mu_\alpha = -3.5$ and $\mu_\delta = -4.6$ milli-arcsec per year. At a distance of 5.5 kpc and a heliocentric velocity of +65 km s$^{-1}$ (Hillwig et al. 2004), we derive velocities relative to the LSR (standard solar motion) of $V^R = -156$, $V^\theta = -57$, $V^z = +30$ km s$^{-1}$, where $R$ is positive radially outward from the Galactic centre, $V^\theta$ is positive in the direction of Galactic rotation, and $z$ is positive toward the North Galactic Pole. For a flat rotation curve at $V^\theta = 220$ km s$^{-1}$, the velocities in a frame corotating at SS 433 thus have peculiar velocities relative to its local standard of rest of -17, +5, +30 km s$^{-1}$, with uncertainties of perhaps 50% in each value. The measurements indicate that the total non-circular motion of SS 433 is small, $\sim 35$ km s$^{-1}$, and directed mainly toward the Galactic plane nearly along the axis of the Western jet.

These results allow us to constrain the history of the system. If the O star binary was created in the Galactic plane and ejected before the SN stage, its age could be $\lesssim 10$ Myr, where the inequality applies if the ejection velocity was more than the minimum needed to achieve its current distance from the plane. Its current space velocity presumably reflects the kick that the system got during the SN, and contains no information on its history prior to the SN. Alternatively, if the supernova occurred in the Galactic plane, and the system was then ejected, its current velocity reflects its dynamical history. It must have reached its greatest distance from the plane, turned around, and now be returning at +30 km s$^{-1}$, which requires a total time of 22 Myr in the Galactic potential of Wolfire et al. (1995).

Another factor is that SS 433 lies at almost the exact centre of W50 measured transverse to the axis of the jets, but is offset by about 4 pc (5') to the west along the jet axis as measured from the peak of the X-ray emission (Watson et al. 1983). Measured from the maximum extent of the radio lobes it is offset in the same direction by about 12 pc. Some asymmetry in the extent of the W50 lobes is expected because they are moving nearly perpendicular to the Galactic vertical density gradient, though in this case there are suggestions that local conditions may be atypical (§8.2). The central part of W50 is, however, quite circular. If we ascribe the offset of SS 433 to its proper motion, it implies a time from the formation of W50 of $1 \times 10^5$ yr. This is identical to the lifetime of SS 433 estimated by Begelman et al. (1980) adjusting their values for a distance of 5.5 kpc, a jet luminosity of $10^{39}$ erg s$^{-1}$ and an ambient density of 0.5 cm$^{-3}$.

We believe it is most likely that SS 433 was formed not
SS 433, its velocity is close to that of the SS 433 system, and the projected jet axis goes precisely through the centre of the H I feature. The jets of SS 433 have a kinetic luminosity \( \sim 10^{39} \text{ ergs s}^{-1} \) (Margon 1984; Panferov & Fabrika 1997), which could supply the necessary energy in \( \sim 10^4 \) years at an efficiency of 10\%. The creation of the shell might have been a brief episode in the life of SS 433, marked now only by the fossil record left in H I. This sequence of events is speculative, but if SS 433 is the source of the shell, the shell age must be \( \sim 10^5 \) yr, about an order of magnitude less than the age derived from simple application of the theory of wind-blown bubbles (Castor et al. 1975) for an object with its properties.

### 8.2 The Static Ring

The static ring is problematic. It is blended with unrelated gas, is not symmetric about SS 433 but is centred on the upper part of W50, and it corresponds to the shape of the radio continuum only along the edge of the western lobe. Indeed, its basic topology is uncertain. Higher resolution H I observations are necessary. There are H I shells observed in the LMC with a size similar to that of the ring, shells with a low expansion velocity as well, but these usually surround OB associations, and may not be relevant to the shell around W50.

Simple application of the equations for wind-blown bubbles (Castor et al. 1975) assuming an expansion velocity of \( \leq 5 \) km s\(^{-1}\), gives the rather large age of \( \geq 10^7 \) yrs. This is comparable to the free-fall time of an object from the location of SS 433 back to the Galactic plane, and is unlikely to be an accurate description of the age of the ring. The theory of bubbles and superbubbles has been reasonably successful when applied to the interstellar structures formed by winds and SN (e.g., Oey 2007), but it does not seem to give reasonable results for the static H I ring associated with SS 433/W50.

### 8.3 The Average Interstellar Density

The average H I density, \( n_0 \), is estimated to be \( 1 - 2 \) cm\(^{-3}\) at the location of the ring around W50 (\( z = -170 \) pc), and 0.4 \(- 1.2 \) cm\(^{-3}\) just below the end of the Eastern jet at \( z = -374 \) pc. These values are more than an order of magnitude greater than the densities expected at these distances from the Galactic plane (Dickey & Lockman 1990). It is interesting that there are other examples of well-defined H I shells which also appear to be expanding into substantially overdense regions (Stil et al. 2004; Gaensler et al. 2003). Perhaps the prominence of W50 in the radio continuum is enhanced because of its accidental location in a large interstellar H I cloud.

### 9 SUMMARY COMMENTS

The new H I absorption data reconcile the kinematic distance to SS 433 with the distance derived from an analysis of light-travel time effects (Blundell & Bowler 2004). Absorption at \( +75 \) km s\(^{-1}\) is detected in two separate measurements at the \( > 10\sigma \) significance level. All data now place SS 433 at a distance 5.5 kpc from the Sun with a systemic velocity...
$V_{LSR} \approx 75 \text{ km s}^{-1}$. The HII region S74 and the molecular cloud at 30 km s$^{-1}$, both of which overlap parts of the W50 remnant, have no association with the system and most likely lie in the foreground, as suspected by [Menon 1954]. We also find no convincing evidence for an association of any HI with W50 at velocities other than near 75 km s$^{-1}$.

The determination of a modest proper motion of 35 km s$^{-1}$ directed nearly along the Western jet (i.e. toward the Galactic plane) suggests that SS 433 originated as an O-star binary which was ejected early in its life from a cluster near the Galactic plane with a velocity away from the Galactic plane $\gtrsim 30$ km s$^{-1}$. The SN of the more massive star then occurred close to where we now observe the system, and in that event it was given a modest kick back toward the Galactic plane. The location of SS 433 near the centre of symmetry of the radio continuum source W50 suggests that the SN occurred 10$^4$ years ago.

There is no molecular cloud (as traced by CO emission) associated with the system, but there seem to be two HI features: a static ring or shell around the upper part of W50, and an expanding shell touching the end of the Eastern lobe. There are many HI shells in the ISM (Menon 1954; Heiles 1973; McClure-Griffiths et al. 2002; Ehlerová & Palouš 2003) often seen surrounding HII regions or clusters of young stars, in other instances without an identifiable source of energy (Stil et al. 2004), but well-developed HI shells around supernova remnants are rare. Studies of individual remnants often show patchy fragmented structures, perhaps because remnants expand into a complex ISM (Koo et al. 1993, 2004; Yar-Uvaniker et al. 2004). It may be significant that the average interstellar density derived for both HI features around W50 is about an order of magnitude greater than what would be expected at their distance from the Galactic plane. This seems to be a trend for some HI shells which are not near regions of star formation (Gaensler et al. 2005; Stil et al. 2004).

The expanding shell is quite interesting, for its measured kinetic energy is so large ($3 \times 10^{49}$ ergs) that it must have been formed by some energetic event, but it is quite far from the Galactic plane and there is no nearby candidate energy source except for SS 433. It is possible that the shell is a fossil remnant of a time when the Eastern jet extended out past the current radio continuum boundaries – the jet has enough energy to create a bubble of this sort in $\sim 10^4$ years. On the other hand, there are examples of HI shells with unidentified energy sources, and it may be a challenge to understand how the kinetic energy of a collimated jet could produce a relatively symmetric expanding shell.

The SS 433 system is ideally situated for the study of the interaction between energetic events and the interstellar medium: it is separated from most confusing sources, accessible at many wavelengths, and has resonably well understood energetics. As noted by [Koníček 1983], the SS 433 jets may offer a unique probe of the ISM. Further study of HI in this region should be rewarding.

ACKNOWLEDGMENTS

The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement with Associated Universities, Inc. We thank Alison Peck for assistance with the VLA observations, Mark Heyer & Chris Brun for obtaining the FCRAO 12CO data and sharing it with us, and Amy Mioduszewski & Michael Rupen for sharing their proper motion data. We also thank Vivek Dwahan, Bob Benjamin, and Mike Shull for useful discussions.

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