THE DISTANCE AND AGE OF THE SUPERNova REMNANTS KES 73 AND AXP 1E 1841-045

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ABSTRACT

We provide a new distance estimate to the supernova remnant (SNR) Kes 73 and its associated anomalous X-ray pulsar (AXP) 1E 1841-045. 21 cm H i images and H i absorption/emission spectra from new VLA observations, and 13CO emission spectra of Kes 73 and two adjacent compact H ii regions (G27.276+0.148 and G27.491+0.189) are analyzed. The H i images show prominent absorption features associated with Kes 73 and the H ii regions. The absorption appears up to the tangent point velocity giving a lower distance limit to Kes 73 of 7.5 kpc, which has previously been given as the upper limit. In addition, G27.276+0.148 and G27.491+0.189 are at the far kinematic distances of their radio recombination line velocities. There is prominent H i emission in the range 80–90 km s⁻¹ for all three objects. The two H ii regions show H i absorption at ~84 km s⁻¹, but there is no absorption in the Kes 73 absorption spectrum. This implies an upper distance limit of ~9.8 kpc to Kes 73. This corrected larger distance to Kes 73/AXP 1E 1841-045 system leads to a refined age of the SNR of 500–1000 yr, and a ~50% larger AXP X-ray luminosity.

Subject headings: Galaxy: structure — H ii regions — ISM: atoms — supernova remnants

Online material: color figure

1. BACKGROUND AND DATA

Because H i atomic clouds are broadly distributed throughout the Galactic plane (Dickey & Lockman 1990), 21 cm H i observations directly provide distance constraints to Galactic plane objects based on an axisymmetric rotation curve model of the Galaxy. However, such a kinematic model causes the near-far kinematic distance ambiguity in the inner Galaxy, i.e., each radial velocity along a given line of sight corresponds to two distances equally spaced on either side of the tangent point. For most Galactic H ii regions where recombination lines are detected, the ambiguity is easily solved by comparison of the radial velocity of the recombination line with the highest velocity of the H i absorption in the H ii region’s direction, because cold H i atomic clouds in front of an H ii region absorb the broad-band thermal bremsstrahlung radio continuum emission from the background H ii region (Kolpak et al. 2003). For other objects of spectral-line radiation, CO observations have helped to reduce the ambiguity, because a CO molecular cloud behind an object will not produce H i absorption feature in the object’s absorption spectrum. As a widely used tool to measure distance, 21 cm H i observations can generally provide a distance estimate to a Galactic object. The methods to construct H i absorption spectra (Dickey & Lockman 1990) can reduce the uncertainty and produce high-sensitivity absorption spectra (due to occasionally patchy distribution, or unsolved emission structure) may cause spurious absorption features, and produce significant uncertainty in the measurement of the absorption spectrum. Faint continuum emission at 1.4 GHz from the target source can also cause too large noise to construct a reliable absorption spectrum. However, the high-resolution observations from interferometers (e.g., Very Large Array [VLA] and Very Long Baseline Array) can reduce the uncertainty and produce high-sensitivity absorption spectra (Dickey & Lockman 1990). There still exists a possibility of significant uncertainties in the absorption spectrum due to the differences in distribution of very small H i clouds along the line of sight-to-source and background regions even using the interferometer’s observations. For H i maps from interferometer data, one has a nearly unlimited choice of source regions and background regions; however, it makes the most sense to minimize the differences in H i distribution between the source region and the background regions by choosing them to be adjacent. In any case, CO observations, however, can help to reduce and explain the uncertainties of the H i absorption spectra, because CO emission spectra can show different emission features along either source or background line of sight (especially sensitive to small high brightness-temperature CO clouds).

Kes 73 is a very young and small (4′ diameter) shell-type radio supernova remnant (SNR) with clumpy X-ray emission and a compact central source (Helfand et al. 1994). The central source of Kes 73, 1E 1841-045, was discovered to be an anomalous X-ray

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pulsar (AXP) by its 11.8 s pulsations and high spin-down rate (Vasisht & Gotthelf 1997) and young characteristic age, ∼4.7 kyr. Further observations confirmed that it is an AXP with a super-strong magnetic field (∼7 × 10^{14} G; Gotthelf & Vasisht 1999). AXPs and soft gamma-ray repeaters are interpreted as magnetars (Thompson & Duncan 1996). For an alternate explanation of the AXP and SGR phenomena involving accretion of a fall-back crust onto a quark star, see Ouyed et al. (2007) for the case of a magnetically supported shell and Ouyed et al. (2006), for the case of a rotationally supported torus.

Based on the analysis of the X-ray spectrum of Kes 73, Gotthelf & Vasisht (1997) inferred an age for the SNR of <2.2 kyr, which is less than half the characteristic age of AXP 1E 1841-045: this emphasizes the inaccuracy of characteristic age as a measure of true age. The distance to Kes 73 was determined by Sanbonmatsu & Helfand (1992) to be in the range of 6–7.5 kpc by means of a 21 cm H i absorption measurement. They employed a commonly used technique to determine distance, by comparing an absorption spectrum toward Kes 73 with absorption seen toward a nearby bright source. However, this technique must be used with care, since there may be significant differences between the distributions of H i along the line of sight to the target source and the comparison source. In this case, multiple comparison lines of sight can determine the correct distance.

In this paper, we revise the distance to Kes 73 based on the H i absorption and emission spectra and 13CO spectra of Kes 73 and nearby sources. The data that we use come from the 1420 MHz continuum and H i–line observations of the VLA Galactic Plane Survey (Stil et al. 2006; Tian et al. 2007b) and from the 13CO–line (J = 1–0) observations of the Galactic ring survey (Jackson et al. 2006). The VLA Galactic Plane Survey data was taken with the VLA in D-array configuration, with synthesized beamwidth of 60”, spectral resolution of 1.56 km s^{-1}, channel width of 0.824 km s^{-1}, and the noise per velocity channel of 2 K. Total bandwidth of the observations centered at 1420.4058 MHz is 1.4 MHz. The center velocity was set at v_c(l) = +80 – (1.6l) for each longitude. The spectra has velocity width of 341 km s^{-1}. Each single observation of a survey field has integration time of 200 s.

2. ANALYSIS AND RESULTS

Figure 1 shows the 1420 MHz continuum image (top left) of Kes 73 and two nearby H ii regions (G27.276+0.148 and G27.491+0.189). It also shows the H i emission at 84 km s^{-1}.

**Fig. 1.**—(a) 1420 MHz continuum image of Kes 73, and the images of H i emission at (b) 84, (c) 107 and (d) 114 km s^{-1}, respectively. The H i maps have superimposed contours (28, 40, 60, 100 K) of the 1420 MHz continuum emission to show the SNR and H ii regions. The solid and dashed lines in (a) show the source and background areas for the H i spectra from boxes 1, 2, and Kes 73. [See the electronic edition of the Journal for a color version of this figure.]
Fig. 2.—H\textsubscript{i} spectra of Kes 73 (top left), G27.276+0.148 (compact source 1, middle left), and G27.491+0.189 (source 2, middle right). The $^{13}$CO emission spectrum of Kes 73 is shown at the top right. The details of the emission and absorption spectra of the three regions are shown at bottom left (c) and bottom right (f), respectively.
(top right), 107 km s\(^{-1}\) (bottom left), and 114 km s\(^{-1}\) (bottom right), respectively. The H\(_i\) image at 107 km s\(^{-1}\) shows clear absorption features associated with Kes 73 and the two H\(_\alpha\) regions. At 114 km s\(^{-1}\), the H\(_i\) distribution is quite inhomogeneous: there is bright emission at the position of G27.276+0.148 (the depression here is due to H\(_i\) absorption against G27.276+0.148); but at the positions of Kes 73 and G27.491+0.189 the H\(_i\) emission is much fainter. The H\(_i\) images in the whole velocity range show that absorption features associated with the supernova remnant Kes 73 and the two H\(_\alpha\) regions appear up to the tangent point velocity (~110 km s\(^{-1}\)), revealing that all three objects are located beyond the tangent point. So the lower distance limit to Kes 73 is 7.5 kpc, assuming a circular Galactic rotation curve model with the IAU adopted value of solar circular velocity \(V_0 = 220\) km s\(^{-1}\) and galactocentric radius of the Sun \(R_0 = 8.5\) kpc. At 84 km s\(^{-1}\), bright H\(_i\) emission covers Kes 73 and the two H\(_\alpha\) regions: there are clear H\(_i\) absorption depressions at the positions of the two H\(_\alpha\) regions but no depression at Kes 73. This implies that the H\(_i\) at 84 km s\(^{-1}\) is at the far kinematic distance, since Kes 73 shows absorption up to the tangent point velocity. It also implies that Kes 73 is in front of the H\(_i\) at 84 km s\(^{-1}\), and the two H\(_\alpha\) regions are behind it.

We confirm the above conclusions using the H\(_i\) emission and absorption spectra and the \(^{13}\)CO emission spectra of Kes 73, G27.276+0.148, and G27.491+0.189. The full velocity range absorption spectra are shown in Figures 2a, 2c, and 2d.

The errors in these spectra are systematic and not statistical, so are best estimated by the fluctuations in the spectra at velocities where there is no real emission or absorption. For the emission spectra, the errors per channel are about 2 K. For the absorption spectra, the errors in e\(^{-}\) depend on the strength of the continuum emission. Here the errors in e\(^{-}\) are ~0.08 for Kes 73, ~0.1 for compact source 1, and ~0.04 for compact source 2.

Details of the emission and absorption spectra of the three regions are shown by Figures 2e and 2f for the velocity range 80–140 km s\(^{-1}\). Figure 2e shows that the H\(_i\) emission in the directions of Kes 73 and compact source 2 decreases in the same way, in the velocity range 104–115 km s\(^{-1}\). Given a velocity dispersion for the H\(_i\) gas of ~5 km s\(^{-1}\), this yields a tangent point velocity of ~110 km s\(^{-1}\). Compact source 1 follows the same trend but has an additional extra (~10 km s\(^{-1}\) wide) H\(_i\) emission component centered on a velocity of ~115 km s\(^{-1}\). Figure 2f shows the three H\(_i\) absorption spectra. These show absorption up to the tangent point velocity for all three directions, showing all three objects are beyond the tangent point. We note that the absorption at 115 km s\(^{-1}\) in compact object 1 is consistent with the extra H\(_i\) emission near that velocity (seen in Fig. 2e), which is not related to the tangent point. Figure 1d clearly shows an extended H\(_i\) filament causing both this extra emission and the extra absorption feature for compact source 1.

Prominent H\(_i\) emission at ~84 km s\(^{-1}\) with no associated absorption is present in the Kes 73 H\(_i\) spectra. This limits the distance of Kes 73 between the far distance for 84 km s\(^{-1}\) and the distance of the tangent point. H\(_i\) emission in the same velocity range (80–90 km s\(^{-1}\)) appears in the emission spectra of both H\(_\alpha\) regions. In this velocity range there is obvious absorption, showing that both H\(_\alpha\) regions are behind this gas. We also find that a CO cloud (at 89 ± 2 km s\(^{-1}\)) in the direction of Kes 73 is behind Kes 73, since it produces no respective H\(_i\) absorption. This cloud shows absorption in the spectra of the H\(_\alpha\) regions, consistent with the conclusions from the H\(_i\) spectra that the H\(_\alpha\) regions are behind the gas in this velocity range. The recombination-line velocities of the two H\(_\alpha\) regions have been obtained previously (Lockman 1989). Our results show that the two H\(_\alpha\) regions are located at the far kinematic distance of their recombination-line velocities (i.e., 36.1 ± 0.4 km s\(^{-1}\) for G27.276+0.148 and 34.0 ± 0.8 km s\(^{-1}\) for G27.491-0.189).

In summary, the H\(_i\) and CO spectra provide strong support to Kes 73 being located beyond the tangent point in the velocity range >89 km s\(^{-1}\). In the circular rotation model with \(V(R) = 220\) km s\(^{-1}\) for all galactocentric distances \(R\) and \(R_0 = 8.5\) kpc, this gives upper and lower distance limits for Kes 73 of 9.8 and 7.5 kpc.

3. DISCUSSION

The distance to Kes 73 in the galactic circular rotation model is 7.5–9.8 kpc, revised upward from the values of 6–7.5 kpc also based on the same rotation model (Sanbonmatsu & Helfand 1992). However, the Galaxy is likely to have noncircular motions due to the presence of a galactic bar and due to spiral arm velocity perturbations. The observed velocity field of the outer galaxy has been studied by Brand & Blitz (1993), but this does not cover the inner galaxy region of interest for Kes 73. Thus one must rely on methods such as modeling the I-V diagram using a galactic gravitational potential, as done in Weiner & Sellwood (1999). Figure 8 of Weiner & Sellwood (1999) shows their resulting radial velocity distribution in the inner 8 kpc by 8 kpc region of the Galaxy. Using our limits for Kes 73 (>89 km s\(^{-1}\) and on the far side of the tangent point), we find distance limits of 7.1 kpc < \(d\) < 8.1 kpc. These are reduced from the circular rotation model values since the velocity contours in the Weiner & Sellwood model are shifted toward the Sun in this region by 0.4–1.5 kpc.

However, the Weiner & Sellwood model predicts a tangent point velocity of 100 km s\(^{-1}\) in the direction of Kes 73 (\(l = 27.4^\circ\)), whereas our H\(_i\) spectra clearly show emission and absorption out to at least 110 km s\(^{-1}\). Using a flat circular rotation curve model with constant \(V(R) = 220\) km s\(^{-1}\) yields a tangent point velocity of 119 km s\(^{-1}\) at \(l = 27.4^\circ\). If we use a more complex circular \(V(R)\) for \(R < R_0\), such as the one in Weiner & Sellwood (1999) with \(V(R_0) = 220\) km s\(^{-1}\) and \(V(R \sim 4\) kpc) = 200 km s\(^{-1}\), we obtain a tangent point velocity of 99 km s\(^{-1}\). The observed H\(_i\) spectra indicate a tangent point velocity of ~110 km s\(^{-1}\), which is obtained with circular rotation and \(V(R \sim 4\) kpc) = 210 km s\(^{-1}\). In this last case, which is the most consistent with our observations, the distance to the point at 89 km s\(^{-1}\) is 9.4 kpc, so that Kes 73 is located between 7.5 and 9.4 kpc.

Next we discuss implications of the revised distance, which we write as \(d_{8.5} = d/8.5\) kpc. Kes 73 is nearly circular in X-rays with a diameter of 4.5\', which is best determined from the Chandra image of Kes 73 (Morii et al. 2003). This is consistent with the determination using ROSAT High Resolution Imager and radio images (Helfand et al. 1994). Kes 73 is likely to be the result of a Type II SNe, with progenitor massive enough to produce a magnetar. Expansion velocities for Type II SNe range from ~5000 to 10000 km s\(^{-1}\). These serve as upper limits to the actual expansion velocity of Kes 73 and yield the lower limits to age of 1100\(d_{8.5}\) yr and 540\(d_{8.5}\) yr, respectively. The mass of swept-up interstellar medium (ISM) for Kes 73 is \(M_{sw} = 23d_{8.5}^2 n_{\odot}\) with \(n_{\odot}\), the ISM density in units of cm\(^{-3}\), so if Kes 73 has an ejecta mass \(M_\odot\) of a few \(M_\odot\), the remnant should be well into the transition to the adiabatic expansion phase. The Sedov model gives lower limits to the shock velocity and upper limits to the age. Using a Sedov model to reproduce the observed radius, with explosion energy \(E\) and electron \(\epsilon = E/(10^{51} \text{ erg})/1n\), yields age 1100\(d_{8.5}^{-1}\) \(\epsilon^{-0.5}\) yr. This also predicts a shock temperature of \(4.4d_{8.5}^{-3}\) keV and shock velocity of \(2100d_{8.5}^{-1}\epsilon^{-0.5}\) km s\(^{-1}\). The
measured X-ray spectrum of Kes 73 (Gotthelf & Vasisht 1999) has an electron temperature of \( \sim 0.7 \text{ keV} \), but this is likely an underestimate of the shock (ion) temperature due to lack of electron-ion equilibration. The alternate of a shock temperature of \( \sim 0.7 \text{ keV} \) can be achieved, if we adjust \( \epsilon \) to 0.16, i.e., either reduce explosion energy or increase ISM density by a factor of 6. For this case, this increases the age to 2600 yr.

In summary, for standard explosion energy and ISM density \( n = 1 \) (\( \epsilon = 1 \)), the upper (Sedov) age limit is 1100 yr and the lower (free expansion) age limit is 500–1000 yr. If, instead, electron-ion equilibration is assumed, the upper age limit increases to 2600 yr and the explosion energy divided by ISM density is very low (\( \epsilon = 0.16 \)). The emission lines detected in Kes 73 argue for ejecta-dominated emission (Gotthelf & Vasisht 1997), so that \( M_{\text{sw}} < M_{\text{ej}} \). This implies \( n < 1 \) so that for a normal explosion energy, the parameter \( \epsilon \) is also larger than 1. This gives an upper age limit of \( \sim 1100 \text{ yr} \), so that the actual age of Kes 73 is likely 500–1000 yr.

The main results here are a larger distance to Kes 73 and a younger age than those previously inferred. The young age (500–1000 yr) raises the possibility that Kes 73 was observable as a historical supernova between 1000 and 1500 AD. If it had a typical maximum-light absolute \( V \) magnitude for Type II SNe of \( -17 \) to \( -18 \), its maximum-light \( V \) magnitude at 8.5 kpc would be \( \sim -3 \), uncorrected for extinction. The visual extinction derived from the X-ray column density of \( 2 \times 10^{22} \text{ cm}^{-2} \) (Gotthelf & Vasisht 1997) is \( A_V \sim 12 \) magnitudes, resulting in a maximum light \( V \) magnitude of \( \sim 9 \), so that this SN would not have been noticed during the time period it likely exploded. The larger distance implies a larger X-ray luminosity for AXP 1E 1841-045 than previously quoted, by a factor of \( (8.5/7)^2 \sim 1.5 \). This implies a somewhat larger magnetic field decay rate in the magnetar model or larger accretion rate in accretion based models than for the luminosity based on the previous smaller distance for Kes 73/ AXP 1E 1841-045. The tighter constraint on age of Kes 73 (500–1000 yr) further supports the arguments of Gotthelf et al. (1999) that AXP 1E 1841-045 is the youngest of the currently known AXPs and soft gamma-ray repeaters (SGRs), and it also raises the question of whether AXP 1E 1841-045 is in a pre-SGR phase, so that we might expect a very active SGR phase from this object in the next several thousand years.

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