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VLBA DETERMINATION OF THE DISTANCE TO NEARBY STAR-FORMING REGIONS. VI. THE DISTANCE TO THE YOUNG STELLAR OBJECT HW 9 IN CEPHEUS A

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ABSTRACT

Using the Very Long Baseline Array (VLBA), we have observed the radio continuum emission from the young stellar object HW 9 in the Cepheus A star-forming region at 10 epochs between 2007 February and 2009 November. Due to its strong radio variability, the source was detected at only four of the ten epochs. From these observations, the trigonometric parallax of HW 9 was determined to be $\pi = 1.43 \pm 0.07$ mas, in excellent agreement with a recent independent determination by Moscadelli et al. of the trigonometric parallax of a methanol maser associated with the nearby young stellar source HW 2 ($\pi = 1.43 \pm 0.08$ mas). This concordance in results, obtained in one case from continuum and in the other from line observations, confirms the reliability of VLBA trigonometric parallax measurements. By combining the two results, we constrain the distance to Cepheus A to be 700^{+31}_{-28} pc, an uncertainty of 3.5%.

Key words: astrometry – magnetic fields – radiation mechanisms: non-thermal – radio continuum: stars – stars: individual (HW 9) – techniques: interferometric

1. INTRODUCTION

The Cepheus A region is an active site of Galactic star formation, which contains one of the very few well-documented examples (HW 2) of a high-mass protostellar system where a disk-like flattened structure has been detected (Patel et al. 2005). The distance to Cepheus A has traditionally been very uncertain with estimates ranging from 300 pc (Migenes et al. 1992) to 900 pc (Moreno-Corral et al. 1993). Recently, Moscadelli et al. (2009) obtained a direct parallax measurement based on multi-epoch observations of a methanol maser feature associated with HW 2, using the Very Long Baseline Array (VLBA) telescope. The corresponding result ($d = 700 \pm 40$ pc) significantly reduced the uncertainty on the distance to Cepheus A, but was based on a single set of observations of a single source. In the present paper, the sixth of our series dedicated to VLBA determinations of distances to nearby star-forming regions (see Loinard et al. 2005, 2007, 2008; Torres et al. 2007, 2009; Dzib et al. 2010 for the previous papers of the series), we will provide an entirely independent measurement of the distance to Cepheus A based on multi-epoch observations of the continuum emission associated with the radio source HW 9.

HW 9 was first reported by Hughes (1991) as the ninth radio source in Cepheus A (following previous detections in the same region reported in Hughes & Wouterloot 1984). Hughes (1991) found that the source was very compact as well as highly variable, and interpreted its radio emission in terms of gyrosynchrotron radiation (see also Hughes et al. 1995 and Garay et al. 1996). In high angular resolution maps (Figure 1), HW 9 appears as an isolated, featureless source located about 5″ to the southeast of the well-studied high-mass object HW 2. The visual extinction toward HW 9 is at least 23 mag (Pravdo et al. 2009) and could be as high as 100 mag (Hughes 1991; Pravdo et al. 2009). As a consequence, no infrared or visual counterpart has ever been reported for HW 9, no spectral classification is available, and the very nature of the source remains very unclear. Because of its possible association with an H II region, Hughes (1991) proposed that HW 9 might be a B3 star. Garay et al. (1996), however, argued that HW 9 is more likely to be a low-mass stellar object because of its radio flaring activity. The observations reported in this paper will provide some additional constraints on the nature of this enigmatic source.

2. OBSERVATIONS AND DATA REDUCTIONS

In total, 10 continuum observations collected at a wavelength of 3.6 cm ($\nu = 8.42$ GHz) will be reported here. The first one (obtained in 2007 February) was designed as a detection experiment. Following the successful detection of the source in that first observation, we initiated a series of nine observations starting in 2007 October. The separation between successive observations in this subsequent data set was about three months, so the last observation occurred in 2009 November. Our main phase calibrator for all epochs was J2302+6405, located at an angular distance of 2°.19 from the target. To improve the quality of phase calibration, we also observed secondary phase calibrators. For the first epoch, we used the quasars J2258+5719, J2223+6249, and J2322+6911 (at angular distances of 4°.72, 3°.90, and 7°.63, respectively, from the target). For the last nine observations, J2322+6911 was replaced by the somewhat more nearby quasar J2309+6820 at 6°.45 from the target (see Figure 2 for the relative positions of the calibrators). The faint quasar J2254+6209, located at 0°.26 from HW 9, was also observed during the last nine observations. It could not be used as a calibrator because it is faint, resolved, and variable, but provided a very useful check on the overall quality of the astrometry.

Each observation consisted of a series of cycles with 2 minutes spent on source, and 1 minute spent on the main phase calibrator J2302+6405. Roughly every 30 minutes, we observed the secondary calibrators, spending 1 minute on each. In addition, geodetic blocks consisting of observations of about two dozen calibrators spread over the entire visible sky were collected at the beginning, the middle, and the end of each of our multi-epoch observations. With these overheads, 5 and 3 hr were

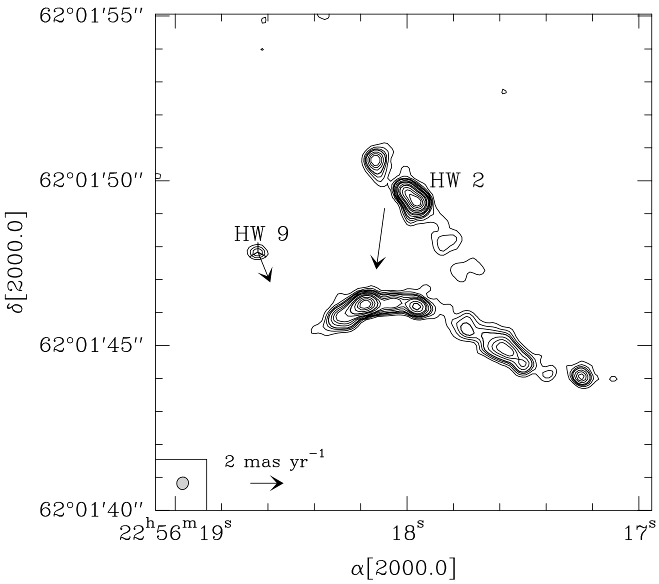

Figure 1. Central region of Cepheus A observed with the VLA in A configuration at $\nu = 4.86$ GHz on 2006 February 11 (project AC810). The data were downloaded from the VLA archive and calibrated following standard procedures. The angular resolution is about 0.″4, and the contours are at −3, 3, 6, 9, 12, 18, 24, 30, 45, 60, 90, 120, and 150 times the noise level in the image ($\sigma = 20\ \mu$Jy beam^{-1}). The arrows represent the proper motions of HW 9 and of the maser associated with HW 2 reported by Moscadelli et al. (2009).

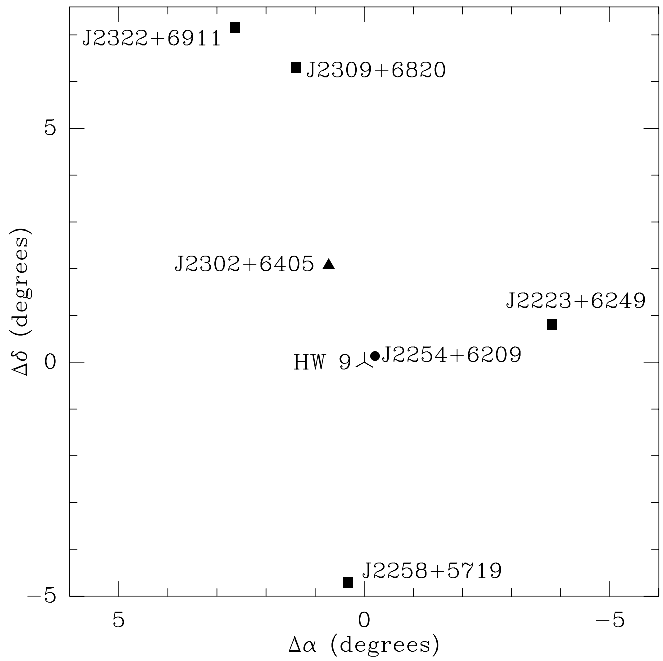

Figure 2. Positions of the main and secondary calibrators relative to the target position; they are plotted as a solid triangle and solid squares, respectively. The faint quasar J2254+6209 was used to check on the overall quality of the astrometry and is shown as a solid circle.

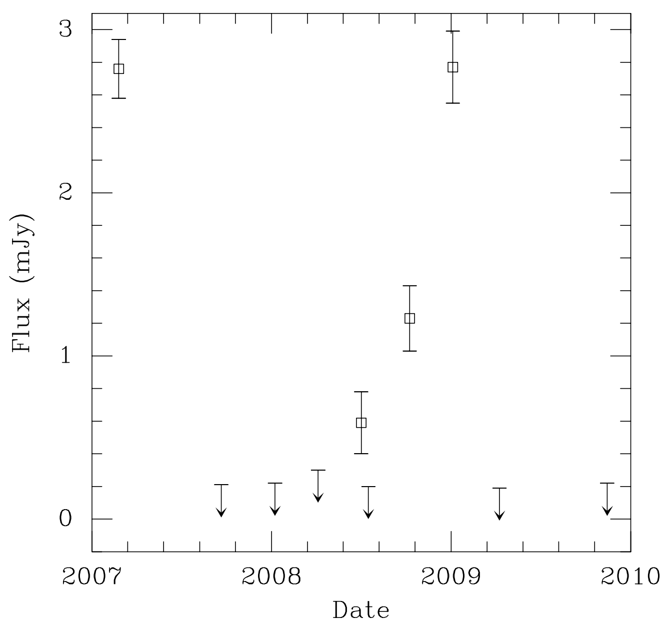

Figure 3. Radio fluxes at 3.6 cm of HW 9 during the 10 observed epochs. The detections were obtained at epochs 2007.20, 2008.50, 2009.77, and 2009.01. The upper limits correspond to 3σ.

spent on source during the first observation and each of the subsequent epochs, respectively. The data were edited and calibrated using the Astronomical Image Processing System (AIPS; Greisen 2003). The basic data reduction followed the standard VLBA procedure for phase-referenced observations, including the multi-calibrator schemes and tropospheric and clock corrections. These calibrations were described in detail by Loinard et al. (2007), Torres et al. (2007), and Dzib et al. (2010). After their calibration, the visibilities were imaged with a pixel size of 50 μas using a weighting scheme intermediate between natural and uniform (ROBUST = 0 in AIPS). The rms noise levels in the final images were 0.08–0.12 mJy beam^{-1}. From these images, the source position was determined using a two-dimensional fitting procedure (task JMFIT in AIPS).

3. RESULTS

HW 9 was detected in four of the ten observed epochs. These detections imply brightness temperatures reaching 10^8 K and clearly demonstrate that the radio emission is of non-thermal (presumably gyrosynchrotron) origin. The source is very variable, reaching a maximum flux of about 2.8 mJy in the first and eighth epochs (Figure 3) while remaining undetectable at levels below ∼0.22 mJy in several observations. This corresponds to a maximum-to-minimum flux ratio in excess of at least 14. The combination of the high brightness and variability of the radio emission indicates that HW 9 is a flaring star with coronal emission, as previously suggested (e.g., Garay et al. 1996).

The positions of HW 9 measured from our VLBA observations were modeled as a combination of a trigonometric parallax (π) and proper motion (μ : assumed to be uniform) following Loinard et al. (2007). The barycentric coordinates of the Earth as well as the Julian date appropriate for each observation were calculated using the Multi-year Interactive Computer Almanac (MICA) distributed as a CD ROM by the US Naval Observatory.

The reference epoch was taken at JD 2454590.95 ≡ J2008.36, the mean epoch of our detections. The best fit to the data (Figure 4) yields the following astrometric elements:

$$\alpha_{J2008.36} = 22^{h}56^{m}18\overset{s}{.}64308 \pm 0\overset{s}{.}00001$$
$$\delta_{J2008.36} = 62^{\circ}1'47\overset{''}{.}83902 \pm 0\overset{''}{.}00005$$
$$\mu_\alpha \cos\delta = -0.76 \pm 0.11 \text{ mas yr}^{-1}$$
$$\mu_\delta = -1.85 \pm 0.04 \text{ mas yr}^{-1}$$
$$\pi = 1.43 \pm 0.07 \text{ mas.}$$

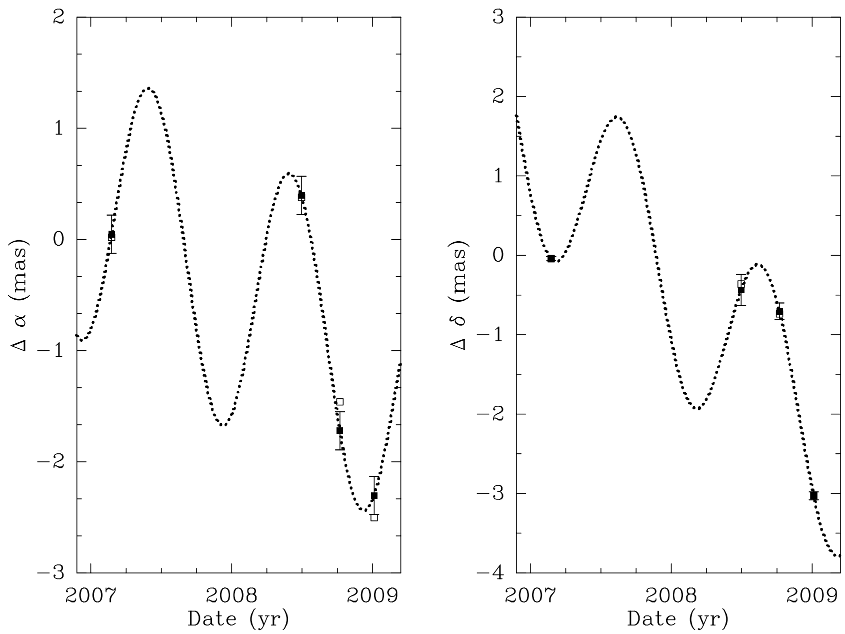

Figure 4. Observed positions (open squares) in right ascension (left panel) and declination (right panel) for the four epochs when HW 9 was detected. The dotted curves show the best fit with a combination of trigonometric parallax and uniform proper motion, and the filled squares show the expected position of HW 9 at the four detected epochs according to the best fit.

The post-fit rms is 0.04 mas in declination, indicating that no systematic errors remain along that axis. In right ascension, however, a systematic contribution of 0.15 mas has to be added quadratically to the errors given by JMFIT to yield a reduced χ^2 of 1. These systematic errors might be related to the east–west structure present in the images of the main phase calibrator and have been included in all the uncertainties quoted in the present paper.

4. DISCUSSION

4.1. Distance and Proper Motion of Cepheus A

The parallax found here for HW 9 is in excellent agreement with the value found by Moscadelli et al. (2009) for a methanol maser associated with the source HW 2 in Cepheus A ($\pi = 1.43 \pm 0.08$ mas). This concordance between two independent results confirms the reliability of VLBA (and, more generally, of very long baseline interferometry, VLBI) measurements of trigonometric parallaxes. By combining the two results, we constrain the parallax of the Cepheus A region to be 1.43 ± 0.06, corresponding to a distance $d = 700^{+31}_{-28}$ pc.

The astrometry carried out by Moscadelli et al. (2009) yielded accurate proper motions for a methanol maser associated with the massive young stellar object HW 2. The velocity of such masers are usually believed to agree with that of their associated young stars to better than 3 km s^{-1} (Moscadelli et al. 2002, 2009). The best proper motion obtained by Moscadelli et al. (2009) for the methanol maser in the HW 2 region was $\mu_\alpha \cos\delta = 0.5 \pm 1.1$ mas yr^{-1} and $\mu_\delta = -3.7 \pm 0.2$ mas yr^{-1}. By comparing these figures with our own results (Section 3), it can be seen that the proper motions of HW 2 and HW 9 are consistent within 1σ in right ascension, but differ by more than 3σ in declination (see Figure 1). The difference ($\Delta\mu_\delta$) corresponds to a velocity difference $\Delta v = 6.2 \pm 0.7$ km s^{-1}, which likely reflects the combination of (1) a $\sim$3 km s^{-1} difference between the velocity of HW 2 and that of its associated maser, and (2) a few km s^{-1} difference between the space velocities of HW 2 and HW 9 due to the expected velocity dispersion within the Cepheus A region.

4.2. Depth of the Cepheus–Cassiopeia Complex

Using VLBI Exploration of Radio Astrometry (VERA) observations of water masers, Hirota et al. (2008) estimated the distance ($d = 764 \pm 27$ pc) to the young massive stellar object IRAS22198 + 6336. In projection, this source is located at 4°.4 (about 55 pc) from Cepheus A and both regions are part of the Cepheus–Cassiopeia molecular cloud complex. The difference in distance appears to be similar to the separation on the plane of the sky, suggesting that the Cepheus–Cassiopeia is about as deep as it is wide. We note that similar depths have been found for other molecular cloud complexes (i.e., Straižys et al. 2003).

4.3. On the Nature of HW 9

As mentioned in Section 1, the exact nature of HW 9 remains unclear. The present detection with the VLBA clearly demonstrates that the radio emission is of non-thermal origin and traces a flaring corona. This is in agreement with previous analyses of Very Large Array (VLA) observations (e.g., Garay et al. 1996) and with the interpretation proposed by Pravdo et al. (2009) of the X-ray emission toward HW 9. High-mass stars are not expected to power active coronas because they are fully radiative. As a consequence, the dynamo mechanism cannot operate in their interior and they do not generate the strong magnetic fields required to maintain a corona.[4] Our observations, therefore, indicate that HW 9 is either a low-mass (T Tauri) or an intermediate-mass (Herbig Ae/Be) young star.

For T Tauri stars, the X-ray and radio emissions appear to be well correlated (e.g., Benz & Guedel 1994). The typical X-ray to radio luminosity ratio for these objects is

[4] The star S1 in Ophiuchus is a fairly massive B4 star which does generate non-thermal radio emission easily detectable with the VLBA. That radio emission, however, appears to show only very moderate variability (unlike that of HW 9) and results from a different type of activity (Loinard et al. 2008; André et al. 1988, 1991).

$L_X/L_R \sim 10^{15.5}$ Hz, with a dispersion around the relation of about 1 dex (Güdel 2004; Benz & Guedel 1994). For Herbig Ae/Be stars, on the other hand, Hamidouche et al. (2008) found a relation $L_X/L_R \sim 10^{11}$–10^{12} Hz, but with a significant dispersion. In particular, values of L_X/L_R as high as 10^{13} Hz were found. Using radio observations with lower angular resolution than those presented here, Pravdo et al. (2009) found $L_X/L_R = (0.2\text{–}1.4) \times 10^{14}$ Hz for HW 9. Combining the data presented here with the X-ray observations of Pravdo et al. (2009), we find a similar L_X/L_R ratio of $(0.1\text{–}0.8) \times 10^{14}$ Hz. This places HW 9 near the lower end of the L_X/L_R relation for T Tauri stars and near the upper end of the relation for Herbig Ae/Be stars. Our observations, therefore, do not strongly constrain the mass of HW 9 beyond the fact that it is not a massive object.

The Cepheus A region is a site of very recent star formation; HW 2, in particular, is believed to be a very young stellar object. The source HW 9 studied here is located only 5″ (less than 0.02 pc) away and is very likely to be coeval with HW 2. The very high extinction toward HW 9 mentioned in Section 1 further reinforces the idea that it is a highly embedded, very young object. Indeed, Pravdo et al. (2009) suggested that HW 9 might be a Class 0/I protostellar object. Evidence for magnetic activity around such young objects has been reported in a limited number of cases (see Güdel 2002, for a discussion). We note, however, that coronal radio emission has never been detected from Class 0 sources and has been conclusively established for only a few Class I objects (Forbrich et al. 2007; Dzib et al. 2010). The likely reason for this paucity is related to the existence around very young objects of partially ionized winds which generate optically thick free–free radio emission surrounding the young stellar source. Any non-thermal coronal radio emission from the young star itself would be absorbed in the optically thick layers of the winds and would never reach the observer. The amount of free–free emission associated with HW 9, however, appears to be very limited. In particular, VLA observations at 6 cm have sometimes failed to detect emission from HW 9 at levels of about 0.15 mJy (Hughes & Wouterloot 1984; Garay et al. 1996). Thus, if HW 9 is indeed a very young object, it is one with very limited ejection activity, and this lack of strong winds would help explain the presence of the coronal emission detected here.

5. CONCLUSIONS

In this paper, we reported on VLBA observations of the young stellar object HW 9 in the Cepheus A star-forming region. These data have been used to provide an independent confirmation that Cepheus A is located at a distance of 700 pc and to reduce the uncertainty on that distance from about 40 pc down to about 30 pc. While it is clear that HW 9 is young and less massive than $\sim 6\,M_\odot$, its exact nature remains unclear. In particular, its radio properties are intermediate between those of low-mass T Tauri stars and those of intermediate mass Herbig Ae/Be objects.

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REFERENCES

André, P., Montmerle, T., Feigelson, E. D., Stine, P. C., & Klein, K. L. 1988, ApJ, 335, 940
André, P., Phillips, R. B., Lestrade, J. F., & Klein, K. L. 1991, ApJ, 376, 630
Benz, A. O., & Guedel, M. 1994, A&A, 285, 621
Dzib, S., Loinard, L., Mioduszewski, A. J., Boden, A. F., Rodríguez, L. F., & Torres, R. M. 2010, ApJ, 718, 610
Forbrich, J., Massi, M., Ros, E., Brunthaler, A., & Menten, K. M. 2007, A&A, 469, 985
Garay, G., Ramirez, S., Rodriguez, L. F., Curiel, S., & Torrelles, J. M. 1996, ApJ, 459, 193
Greisen, E. W. 2003, in Information Handling in Astronomy: Historical Vistas, ed. A. Heck (Astrophysics and Space Science Library, Vol. 285; Dordrecht: Kluwer), 109
Güdel, M. 2002, ARA&A, 40, 217
Güdel, M. 2004, A&AR, 12, 71
Hamidouche, M., Wang, S., & Looney, L. W. 2008, AJ, 135, 1474
Hirota, T., et al. 2008, PASJ, 60, 961
Hughes, V. A. 1991, ApJ, 383, 280
Hughes, V. A., Cohen, R. J., & Garrington, S. 1995, MNRAS, 272, 469
Hughes, V. A., & Wouterloot, J. G. A. 1984, ApJ, 276, 204
Loinard, L., Mioduszewski, A. J., Rodríguez, L. F., González, R. A., Rodríguez, M. I., & Torres, R. M. 2005, ApJ, 619, L179
Loinard, L., Torres, R. M., Mioduszewski, A. J., & Rodríguez, L. F. 2008, ApJ, 675, L29
Loinard, L., Torres, R. M., Mioduszewski, A. J., Rodríguez, L. F., González-Lópezlira, R. A., Lachaume, R., Vázquez, V., & González, E. 2007, ApJ, 671, 546
Migenes, V., Cohen, R. J., & Brebner, G. C. 1992, MNRAS, 254, 501
Moreno-Corral, M. A., Chavarria, K. C., de Lara, E., & Wagner, S. 1993, A&A, 273, 619
Moscadelli, L., Menten, K. M., Walmsley, C. M., & Reid, M. J. 2002, ApJ, 564, 813
Moscadelli, L., Reid, M. J., Menten, K. M., Brunthaler, A., Zheng, X. W., & Xu, Y. 2009, ApJ, 693, 406
Patel, N. A., et al. 2005, Nature, 437, 109
Pravdo, S. H., Tsuboi, Y., Uzawa, A., & Ezoe, Y. 2009, ApJ, 704, 1495
Straižys, V., Černis, K., & Bartašiūtė, S. 2003, A&A, 405, 585
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2007, ApJ, 671, 1813
Torres, R. M., Loinard, L., Mioduszewski, A. J., & Rodríguez, L. F. 2009, ApJ, 698, 242