A PARALLACTIC DISTANCE OF $389^{+24}_{-21}$ PARSECS TO THE ORION NEBULA CLUSTER FROM VERY LONG BASELINE ARRAY OBSERVATIONS

KARIN M. SANDSTROM, J. E. G. PEEK, GEOFFREY C. BOWER, ALBERTO D. BOLATTO, AND RICHARD L. PLAMBECK

Department of Astronomy and Radio Astronomy Laboratory, University of California, Berkeley, CA 94720; karin@astro.berkeley.edu

Received 2007 April 23; accepted 2007 June 15

ABSTRACT

We determine the parallax and proper motion of the flaring, nonthermal radio star GMR A, a member of the Orion Nebula Cluster, using Very Long Baseline Array observations. Based on the parallax, we measure a distance of $389^{+24}_{-21}$ pc to the source. Our measurement places the Orion Nebula Cluster considerably closer than the canonical distance of $480 \pm 80$ pc determined by Genzel et al. A change of this magnitude in distance lowers the luminosities of the stars in the cluster by a factor of $\sim 1.5$. We briefly discuss two effects of this change—an increase in the age spread of the pre-main-sequence stars, and better agreement between the zero-age main sequence and the temperatures and luminosities of massive stars.

Subject headings: astrometry — open clusters and associations: individual (Orion Nebula Cluster) — stars: distances — stars: individual (GMR A) — techniques: interferometric

1. INTRODUCTION

The Orion Nebula is the nearest example of ongoing massive star formation. As such, it has an important place in our understanding of this fundamental process. Observations of luminosities, masses, and linear scales in the Orion Nebula all depend on the distance to the cluster. For many years, the most often used distance measurement to Orion has been $480 \pm 80$ pc, as determined by Genzel et al. (1981). The Hipparcos mission was only able to marginally detect the parallax of one star in the cluster, resulting in a distance of $361^{+168}_{-120}$ pc. Other techniques of estimating the distance to the cluster provide values with large uncertainties and systematic errors, but that are generally consistent within the Genzel et al. range.

At the canonical distance of 480 pc, the annual parallax of an object in the Orion Nebula would be about 2 mas. In order to measure this parallax to high precision, angular resolution far in excess of 1 mas is necessary. The Very Long Baseline Array (VLBA) can achieve this degree of angular resolution, and it has thus been a very useful tool for determining parallaxes for radio sources out to a few kiloparsecs (e.g., Brisken et al. 2002; Chatterjee et al. 2004; Hachisuka et al. 2006; Loinard et al. 2005).

In order to obtain a precise measurement of the distance to Orion using VLBI, the target source must be compact and persistent. A number of compact radio sources have been observed in Orion, first by Garay et al. (1987) and later by Felli et al. (1993a) and others. At least 10 of the sources detected by these authors were identified as nonthermal radio stars because of their compactness (unresolved by the VLA A array) and variability (Felli et al. 1993b). Bower et al. (2003) observed one of these sources, GMR A, over the course of an extreme millimeter flaring event, during which its 86 GHz flux density increased by a factor of 5 over a few hours. Follow-up observations with the VLBA detected GMR A at 15 and 22 GHz with a compact size of less than 1 mas. We obtained five additional epochs of VLBA observations spaced over the following year to monitor the astrometric motion of the source. We detect GMR A in four of those five observations, indicating that this source was persistent enough to allow measurement of its proper motion and parallax, thus determining the distance to Orion in a model-independent manner.

Unlike other published distance measurements to Orion, the parallactic distance presented here is model independent. Genzel et al. (1981) determined a distance of $480 \pm 80$ pc by modeling the proper motions and radial velocities of H$_2$O masers in the Becklin-Neugebauer/Kleinmann-Low (BN/KL) region with an expanding, thick shell—a technique that required assumptions about the geometry of the system of masers. Most other available distance measurements to Orion rely on stellar models in some way. Because the maser distance is independent of stellar properties, it has become the canonical distance to Orion. Recently, Jeffries (2007) has found a distance of $392 \pm 32$ pc based on the statistical properties of rotation in pre-main-sequence stars. In determining this distance, Jeffries (2007) assumes a spectral type–effective temperature scale for pre-main-sequence stars and a random distribution of spin axes. In addition, they also must accurately identify stars that are still in the accretion phase of their pre-main-sequence lifetime. Parallax provides a fundamental measure of the distance, avoiding the systematic uncertainties associated with these other techniques.

Accurate knowledge of the distance to the Orion Nebula Cluster (ONC) is important for the general understanding of star formation in the region. Luminosities are proportional to distance squared, and the ages of pre-main-sequence stars are typically determined by comparing their temperatures and luminosities with theoretical models (for example, Palla & Stahler 1999). Changes in the luminosity of the stars translate directly into changes in their inferred ages, and the age distribution of the pre-main-sequence stars in the cluster is a key component of any model that attempts to explain the mode of star formation in the region.

In § 2.1 we describe the VLBA observations, and in § 2.2 we discuss their reduction. In particular we discuss the use of a dual calibrator method developed by Fomalont (2005). Section 3 covers the analysis of our positions for the source and presents our best-fit values for the parallax and proper motion. In § 4 we discuss how this measurement will affect the study of the Orion Nebula and its star formation and compare our measurement with previous results.

2. OBSERVATIONS AND DATA REDUCTION

2.1. VLBA Observations

The observations were carried out at a frequency of 15 GHz with all available VLBA antennas. There were six epochs of
VLBA observations: an initial observation of the source in 2003 January in the wake of its flaring event, and five epochs evenly spaced over 1 year to adequately sample the entire parallactic ellipse of GMR A.

To determine the astrometric position of GMR A, we use phase referencing to the bright quasar J0541−0541, which is located 1.6° to the southeast of the target. In addition, to account for phase variation due to atmospheric gradients between J0541−0541 and GMR A, we observe a secondary calibrator, J0529−0519, which is 1.3° northwest of GMR A and approximately collinear with GMR A and J0541−0541. The data reduction using these two calibrators in the phase referencing is described in § 2.2. Each observation, excluding 2003 January, consisted of alternating 40 s integrations on the two calibrator sources and on GMR A for 6 hr. The first epoch, 2003 January, was part of a campaign to understand the millimeter and X-ray flare from GMR A at high resolution. The secondary calibrator was not included in this track, which consisted of alternating observations of only GMR A and J0541−0541 for 40 s each. A very bright calibrator, J0530+1331, was observed a few times during the course of each track for use in removing instrumental phase offsets and delays in each intermediate frequency (IF).

2.2. Data Reduction

The data reduction was performed in AIPS. The initial calibrations proceeded as described in the AIPS cookbook for VLBA data reduction. These include amplitude calibration and fringe fitting to determine the instrumental single-band delay (slope of phase vs. frequency introduced by the instrument) and the residual phase delays and rates introduced by the atmosphere and inaccuracies in the correlator model.

Recently discovered errors in the Earth orientation parameters used by the VLBA correlator for all epochs excluding 2003 January were corrected using the task CLCOR, as described in the VLBA Test Memo 69 (Walker et al. 2005). The data were corrected for the single- and multiband delays with the task FRING. The target source is detected at 5σ or greater, in four out of the six epochs using only phase referencing to the main calibrator, J0541−0541. In the 2004 October observation, GMR A is only detected after ATMCA correction, as described below. In 2004 April, there are a number of significant peaks in the image because the flux from GMR A has been scattered by poor phase coherence, probably due to fluctuations in tropospheric water vapor. We have omitted the 2004 April data from the following analysis because of its poor quality.

In order to improve the image quality and remove some systematic errors in the position of the target source we used dual source phase referencing, as implemented in the AIPS task ATMCA (Fomalont 2005). This corrects for phase gradients across the sky due to tropospheric effects. The correction can be done in a number of ways, but in our case we used interpolation between two calibrator sources placed on either side of the target. Prior to ATMCA we also correct for the effects of structure in our calibrators through self-calibration cycles on both sources. It is clear from the images that both calibrators have resolved structure, which makes the self-calibration cycle important for accurate imaging of the target source. We note that the structure of the main calibrator appears to be approximately constant over the time period of our observations. We see at most a few percent variation in the brightness distribution of J0541−0541 comparing between epochs with clean components all restored to the lowest resolution of the five observations. Because of the lack of variation in the source structure and the high signal-to-noise ratio of the calibrator observations, the self-calibration cycle should be sufficient to correct systematic errors in the phase solutions due to the structure of the calibrator. After ATMCA calibration we see an increase in the compactness of GMR A of up to 17%. In addition, in the October data set, the significance of the GMR A detection changes from <4 to 5σ. The effects of the dual source calibration are summarized in Table 3.

After ATMCA, cleaned images of the sources were made using the task IMAGR. In each epoch, we measured the position of GMR A with reference to the main calibration source J0541−0541, for which we assume the J2000.0 position R.A. = 22°54′38.084106″, decl. = −5°14′49.42841″. The position assumed for the secondary calibrator, J0529−0519, in J2000.0 is R.A. = 22°59′53.552715″, decl. = −5°19′41.61564″. This position is used in the course of ATMCA calibration. The five images of GMR A are shown in Figure 1, centered on the maximum point in each image. The images of the calibrators J0541−0541 and J0529−0519 are shown in Figures 2 and 3, respectively. In these figures the positions are relative to the maximum of the image in the 2003 December observation. Positions and fluxes for the secondary calibrator, J0529−0519, are listed in Table 2.

It is clear from the integrated flux densities listed in Table 1 that we observe significant variability in GMR A at 15 GHz. This observation is in line with previous studies that show large changes in the source flux density (Felli et al. 1993b; Zapata et al. 2004; Bower et al. 2003). Bower et al. (2003) postulate that the structure of GMR A consists of a compact, highly variable source that
the VLBA detects and an extended, \(~5\) mJy envelope that is resolved out. Our observations certainly indicate that the source detected by the VLBA is highly variable.

2.2.1. Structure in the VLBI Images of GMR A

The images of GMR A shown in Figure 1 show resolved structure. At the distance we measure to the cluster, stellar photospheres should be unresolved. We can estimate the photospheric radius of GMR A from the bolometric luminosity of \(6\, L_\odot\) and the spectral type K5 V, as determined by Bower et al. (2003) given the effective temperature–spectral type calibration for pre-main-sequence stars of Cohen & Kuhi (1979). This yields a radius of \(\sim 4.3\, R_\odot\), which at the distance of Orion is \(\sim 50\, \mu\text{as}\), well below the resolution of our observations. Since there is resolved structure present in the images, we must consider its source in determining the position of GMR A. Scattering by turbulent interstellar plasma can cause angular broadening. We estimate the effects of interstellar scattering on our images using the Cordes & Lazio (2002) model, which predicts an angular broadening scale at 15 GHz of \(\sim 0.05\, \mu\text{as}\) for the line of sight to the calibrators and \(\sim 2.0\, \mu\text{as}\) for GMR A. The measured sizes of our calibrators are consistent with very little or no interstellar scattering, in agreement with the model predictions. Some of the structure in our images is most likely due to atmospheric calibration errors.

In particular, the correction from ATMCA applies mostly in the right ascension dimension due to the positioning of our two calibrator sources east-west relative to GMR A. It is the case that most of the images are elongated more in the declination dimension compared to the beam shape, suggesting atmospheric effects.

However, there is also more persistent structure, mainly obvious when GMR A is bright. Bower et al. (2003) noted this structure and found that the 2003 January observation could be equally well represented by a Gaussian extended relative to the beam shape, or by two unresolved sources with a separation of 0.8 mas. In the 2003 December and 2004 December observations as well, we see structures that are better represented by two unresolved sources or an extended Gaussian. We considered the possibility of binarity to explain the resolved structure, and we note that if GMR A were a binary, orbital motion would introduce scatter into our solution for the parallax and proper motion. Using the positions determined by fitting two unresolved sources to the images, we attempted to find a mass ratio that gave a center-of-mass position between the two purported sources that decreased the scatter in the parallax and proper-motion solution. Because there is no consistent way to distinguish between the two sources, we also searched through the 16 possible permutations of primary and secondary components. For each of these permutations, we also attempted to fit a relative visual binary orbit using a technique based on that of Hartkopf et al. (1989). We were unable to find a consistent solution that improved the scatter of our parallax and proper motion using these two complementary techniques. Therefore, it seems unlikely that the structure in our images is due to a binary companion.

A more likely explanation for the structure in our images is large-scale magnetic features associated with the star. These have
been observed with VLBI in other magnetically active weak-line T Tauri stars (Phillips et al. 1991; Andre et al. 1992) with sizes of up to (10–20) R\(_\odot\). A separation of 0.8 mas at the distance we measure to Orion corresponds to ~15 R\(_\odot\), which is comparable to structures observed on other weak-line T Tauri stars. We do know that GMR A has a ~2 kG photospheric magnetic field (Bower et al. 2003) and experiences a high level of magnetic flaring activity as seen in X-ray, millimeter, and radio observations, so it seems reasonable to expect large-scale magnetic structures around the star. The effect of the positional jitter introduced in our measurements by imperfectly calibrated atmosphere and by source structure is to increase the error bars in the distance determination.

### 2.2.2. Astrometric Positions of GMR A

If GMR A were unresolved and we could account for the effects of the atmosphere by observing a known point source, the best technique for determining the positions of the target would be to fit a fixed-size Gaussian to the images. However, since GMR A appears to have resolved structure that may vary in time and neither of our calibrators are unresolved, the best technique for determining the source positions is to fit variable size Gaussians to the images. We did this using the AIPS task JMFIT, allowing the dimensions and position angle of the fit Gaussian to vary. Table 4 lists the dimensions of the beam for each observation and the properties of the best-fit Gaussian. The positions derived from these fits are listed in Table 1. As a check, we have also fit the images with a Gaussian constrained to have the shape and size of the beam. The positions we find from these two techniques are consistent within their error bars; however, the positions we determine from fitting the constrained Gaussian have smaller error bars, increasing the \(\chi^2\) of our parallax and proper-motion solution, although it yields the same distance.

In the case of the 2003 January observation, ATMCA cannot be applied, as only one calibrator was observed. To account for any systematic differences in the positions determined with and without ATMCA, we increased the uncertainty of the 2003 January observation by adding the rms effect of ATMCA on the other three observations in quadrature with its observed position errors (85 \(\mu\)as in R.A. and 18 \(\mu\)as in decl.).

### 3. ASTROMETRIC ANALYSIS

The position of GMR A as a function of time is determined by its position, parallax, and proper motion in the following way:

\[
\alpha(t) = \alpha_0 + \mu_\alpha t + \pi f_\alpha(\alpha, \delta, t),
\]

\[
\delta(t) = \delta_0 + \mu_\delta t + \pi f_\delta(\alpha, \delta, t).
\]

Here \(\mu_\alpha\) and \(\mu_\delta\) are the proper motions in right ascension (R.A.) and declination (decl.), respectively, and \(\pi\) is the parallax; \(f_\alpha\) and \(f_\delta\) are the parallactic displacements for a source at a distance of 1 pc at the position of GMR A. The parallactic displacements are calculated based on the formulae presented in the US Naval Observatory Almanac.

To fit to these five positions (10 data points) we employed a \(\chi^2\) fit to five parameters: position in R.A. and decl., proper motion in R.A. and decl., and parallax. The best-fit solution had a reduced \(\chi^2\) value of \(85\). This indicates that our error bars on the position are approximately \(3.2\) times larger than the formal errors from Gaussian fitting, mostly due to systematic effects from tropospheric variations and variability of the source structure. To determine the error bars on the best-fit parallax and proper motion we proceeded in the following way: first, we added systematic errors in quadrature to the error bars listed in Table 1 to achieve \(\chi^2 = 1\); then we used a Monte Carlo simulation in which we added offsets, drawn from a Gaussian distribution centered at zero with a width representing the total positional errors from the previous step, to the measured positions and fit for the astrometric parameters. The resulting distributions of parallax and proper motion were well represented by Gaussians, allowing a straightforward determination of the 1 \(\sigma\) errors.

### Table 1

| Date          | R.A. (J2000.0) | R.A. Error (\(\mu\)as) | Decl. (J2000.0) | Decl. Error (\(\mu\)as) | Noise Level (mJy beam\(^{-1}\)) | Integrated Flux Density (mJy) |
|---------------|---------------|------------------------|----------------|------------------------|-------------------------------|-------------------------------|
| 2003 Jan 29   | 5 35 11.80269059 | 18.44                 | –5 21 49.246612 | 36.48                  | 0.395                         | 11.366 \(\pm\) 0.785         |
| 2003 Dec 22   | 5 35 11.80289569 | 29.89                 | –5 21 49.247830 | 93.57                  | 0.267                         | 6.815 \(\pm\) 0.875          |
| 2004 Jun 12   | 5 35 11.80297711 | 36.82                 | –5 21 49.245846 | 86.22                  | 0.280                         | 4.217 \(\pm\) 0.743          |
| 2004 Oct 15   | 5 35 11.80317743 | 50.88                 | –5 21 49.249019 | 163.29                 | 0.271                         | 2.791 \(\pm\) 0.731          |
| 2004 Dec 11   | 5 35 11.80305845 | 11.47                 | –5 21 49.249589 | 21.66                  | 0.321                         | 23.002 \(\pm\) 0.974          |

*Notes:* Positions measured relative to the assumed J2000.0 position of J0541 – 0541: R.A. = \(5^h41^m38.s084106^s\), decl. = \(-5^h41^m49.42841^s\). The errors listed are the formal errors from Gaussian fitting.
The best approach to adding in systematic errors to achieve $\chi^2 = 1$ is not well defined, so we approach the problem with a few different techniques. To start, we added in quadrature the same systematic error in the R.A. and decl. dimensions until we reached $\chi^2 = 1$. This gave a parallax of $2.53 \pm 0.18$ mas (equivalent to a distance of 395$^{+36}_{-30}$ pc). However, it is most likely not the case that the systematic errors are the same in R.A. and decl. We know that our correction from ATMACA mostly applies in the R.A. dimension, due to the positioning of our calibrators east-west relative to the target. To address the nonuniformity of the systematic errors we added in quadrature error ellipses with varying axial ratios and determined the axial ratio for which the total systematic errors we added in quadrature error ellipses with vary-

The Orion Nebula is part of a very large and very complex star formation region (see Genzel & Stutzki [1989] for a review of the large-scale structure). The implications of a measurement of the distance to one star thus depend sensitively on where that star is located relative to the stellar associations and molecular gas in this region. The available evidence very strongly constrains GMR A to be a part of the Orion Nebula Cluster (ONC), located within a few parsecs of the Trapezium stars but embedded in the molecular cloud, which is currently being disrupted by the ionizing radiation from $\theta^1$ Ori C. In the following paragraphs we present the evidence for placing GMR A in the ONC and then proceed to compare our distance to previous measurements and, finally, briefly discuss some of the implications our distance measurement has for the general study of this important region.

4.1. The Membership of GMR A in the Orion Nebula Cluster

Bower et al. (2003) observed GMR A, following its intense outburst detected with the BIMA interferometer, in the near-IR with NIRC and NIRCSPEC on the Keck telescopes. While there is no optical source coincident with the position of GMR A, there is an IR source that they identify as a weak-line T Tauri star embedded in molecular gas. GMR A was also detected in the COUP survey as a highly variable X-ray source (COUP J053551.8–052149; Feigelson et al. 2002; Getman et al. 2003) behind a gas column density of $N_H = 10^{22.3}$ cm$^{-2}$. The combination of the spectral classification as a K5 V star and a bolometric luminosity of $6 L_{\odot}$ (Bower et al. 2003) suggests a very young age for this star (around 1 Myr, based on the pre-main-sequence tracks of Palla & Stahler [1999]), as does its location embedded in molecular gas.

The molecular gas in Orion A, located behind the H II region created by the Trapezium stars, has a very high column depth $A_V \approx 50–100$ mag, essentially providing a wall behind which no background sources are detected. Near-IR surveys have shown

### Table 3

| Date               | $\Delta_{\text{R.A.}}$ (mas) | $\Delta_{\text{decl.}}$ (mas) | Total Shift (mas) | Percent Change Area$^a$ | Percent Change Peak Flux$^b$ |
|--------------------|-----------------------------|-------------------------------|------------------|-------------------------|-----------------------------|
| 2003 Jan 29........| ...                         | ...                           | ...              | ...                     | ...                         |
| 2003 Dec 22........| $-4.36$                     | 115.92                        | 116.02           | $-13.2$                 | +20.6                       |
| 2004 Jun 12........| $-84.60$                    | 88.92                         | 122.46           | $-17.4$                 | $-15.9$                     |
| 2004 Oct 15........| ...                         | ...                           | ...              | ...                     | ...                         |
| 2004 Dec 11........| $+85.32$                    | 83.16                         | 119.14           | $-11.5$                 | +24.1                       |

$^a$ The area of the source is defined here as $\pi ab$, where the $a$ and $b$ values are the FWHM of the major and minor axes of the best-fit Gaussian, respectively.

$^b$ The peak flux is measured in units of Jy beam$^{-1}$.

### Table 4

| Date               | Beam FWHM (mas $\times$ mas) | Beam P. A. (deg) | Gaussian FWHM (mas $\times$ mas) | Gaussian P. A. (deg) |
|--------------------|-------------------------------|-----------------|----------------------------------|----------------------|
| 2003 Jan 29........| 1.994 $\times$ 0.597          | $-15.52$        | 2.028 $\times$ 0.738             | $-10.00$             |
| 2003 Dec 22........| 1.195 $\times$ 0.448          | $-5.58$         | 2.230 $\times$ 0.619             | $-9.52$              |
| 2004 Jun 12........| 1.122 $\times$ 0.438          | $-3.63$         | 1.682 $\times$ 0.576             | $-14.13$             |
| 2004 Oct 15........| 1.111 $\times$ 0.455          | $-1.04$         | 2.114 $\times$ 0.482             | $-11.81$             |
| 2004 Dec 11........| 1.178 $\times$ 0.473          | $-4.53$         | 1.662 $\times$ 0.800             | $-12.18$             |
that the projected spatial distribution of optically visible and extinguished, near-IR sources are very similar (Hillenbrand & Hartmann 1998), and that around 50% of sources are only visible in the IR. The three-dimensional distribution of the ONC has thus been interpreted as fairly spherical with about half of that sphere still embedded in the molecular cloud out of which it formed (Hillenbrand & Hartmann 1998). The projected distribution of stars has a radius of ~3 pc around θ¹ Ori C. GMR A is located 1.95' away from the center of the cluster, which corresponds to a projected distance of 0.22 pc at our measured distance to the cluster. The X-ray absorption column density measured to GMR A indicates that it must be embedded in the molecular gas, but it cannot be more than a few parsecs deep. The lack of foreground and background star-forming regions, the proximity of GMR A to the Trapezium on the sky, the fact that it is embedded in molecular gas, and its very young age convincingly place GMR A as a member of the ONC.

In addressing the membership of a stellar cluster, a typical technique is to compare the velocity of a star to the average velocity and dispersion of the cluster. There have been a number of measurements of these quantities for the ONC with proper-motion and radial velocity studies. Recent spectroscopic observations of stars in the cluster by Sicilia-Aguilar et al. (2005) show a mean heliocentric velocity of 25 km s⁻¹, with a ~2 km s⁻¹ uncertainty in the zero point and a dispersion of σ = 2.3 km s⁻¹. Bower et al. (2003) measured a heliocentric radial velocity of 14 ± 5 km s⁻¹ for GMR A. Given the combined uncertainties in these measurements and the cluster radial velocity dispersion, GMR A is consistent with the radial velocity of the cluster.

Most proper-motion studies of clusters, including that of Jones & Walker (1988), which surveyed nearly 1000 stars in Orion, measure relative proper motions. In order to compare our measurement, which is an absolute proper motion, to the results of these studies, we must first find the absolute proper motion of the ONC to subtract from our values. This value has been measured by a number of authors using different astrometric catalogs. Baumgardt et al. (2000) use the Hipparcos catalog and measure a mean proper motion of μₚ, cos(δ) = 1.73 ± 0.40 and μₚ = −0.47 ± 0.27 mas yr⁻¹ for the ONC. Kharchenko et al.¹ used the All-Sky Compiled Catalog (ASCC); which contains data from Hipparcos, Tycho, and the US Naval Observatory (USNO) catalogs and found very similar values, μₚ, cos(δ) = 2.02 ± 0.74 and μₚ = −0.19 ± 0.66 mas yr⁻¹. Later, Kharchenko et al. (2005) improved their determination of the absolute proper motion with an expanded astrometric catalog and found μₚ, cos(δ) = 1.96 ± 0.31 and μₚ = −0.77 ± 0.46 mas yr⁻¹. All of these values are consistent within their error bars, so we proceed in our analysis using the recent value of Kharchenko et al. (2005). We measure a proper motion for GMR A of μₚ, cos(δ) = 1.89 ± 0.12 and μₚ = −1.67 ± 0.19 mas yr⁻¹. These values are quite similar to the cluster mean. We can compare the residual velocity after subtracting the mean to the velocity dispersion of the cluster. The velocity dispersion of the ONC has been measured by a number of authors. The largest survey of relative proper motions was carried out by Jones & Walker (1988). They found a one-dimensional proper-motion dispersion of ~1.1 mas yr⁻¹ for all of the cluster stars in their survey (I magnitude of 16 or higher). In addition, they found a trend of decreasing velocity dispersion with increasing mass (and, therefore, magnitude) for stars in the ONC. Hillenbrand & Hartmann (1998) show that for stars with masses between 0.1 and 0.3 M☉ the dispersion is ⟨σ⟩ ≈ 1.26 mas yr⁻¹, and for stars between 1 and 3 M☉ it decreases to 1.00 mas yr⁻¹. The proper motion of GMR A is less than 1 σ from the cluster average, indicating a very high membership probability.

At the distance we measure to the ONC, a velocity of 1 mas yr⁻¹ is equivalent to 1.85 km s⁻¹. Relative to the cluster, GMR A is moving 0.13 ± 0.61 km s⁻¹ west, 1.67 ± 0.93 km s⁻¹ south, and −11.0 ± 5.4 km s⁻¹ along the line of sight. We note that there are large uncertainties in the radial velocity, both for GMR A and for the cluster as a whole. However, even at ~11 km s⁻¹ relative to the cluster, GMR A would only have moved ~10 pc over its lifetime.

There is one measurement of the proper motion of GMR A in the literature by Gomez et al. (2005). They determined the

![Figure 4](image_url)

**Figure 4.** Measured positions of GMR A with the best-fit parallax and proper motion. The diamonds represent the predicted position of GMR A for each observation. The error bars on the measured positions are scaled as described in the text. The dot-dashed line is the proper motion of the source, with the parallactic motion subtracted. The parallax corresponds to a distance of 389 ± 21 pc.

---

**Table 5: GMR A Astrometric Parameters**

| Parameter | Value |
|-----------|-------|
| Epoch     | 2004.25 (MJD 53,095.3) |
| Right ascension α₀          | 5°35′11.80295404′ |
| Declination δ₀               | −5°2′149.2474522′ |
| μα cos(δ) (mas yr⁻¹)         | 1.89 ± 0.12 |
| μδ (mas yr⁻¹)                | −1.67 ± 0.19 |
| Parallax π (mas)             | 2.57 ± 0.15 |

**Derived Quantities**

| Distance (pc) | 389 ± 21 |
| Transverse velocity (km s⁻¹) | 4.65 ± 0.39 |
| Position angle (deg) | 131.5 ± 3.7 |

¹ Vizier Online Data Catalog, J/AZh/80/291 (N. V. Kharchenko, L. K. Pakulyak, & A. E. Piskunov, 2003).
absolute proper motions of 35 radio sources in Orion with archival Very Large Array (VLA) data spanning 15 years. Although we have much higher angular resolution in our observations, their long time baseline makes the comparison useful. They measure the absolute proper motion of the cluster to be \( \mu_x \cos(\delta) = 0.8 \pm 0.2 \) and \( \mu_y \cos(\delta) = -2.3 \pm 0.2 \text{ mas yr}^{-1} \). These values are quite different from others in the literature. The absolute proper motion for GMR A they find is \( \mu_x \cos(\delta) = -2.02 \pm 1.87 \) and \( \mu_y = 1.15 \pm 1.93 \text{ mas yr}^{-1} \). Our measurement is only consistent with these values at the 2 \( \sigma \) level. They find a substantially higher velocity dispersion for the cluster than found in optical surveys and theorize that the population of radio sources might have larger random velocities. However, using our proper motion, GMR A has a very typical velocity compared to the optical sources.

To summarize, GMR A is a very likely member of the ONC based on its youth, proximity to the cluster on the sky, proper motion, and location embedded in molecular gas. Having established its place in the Orion region, we now compare our distance measurement to those in the literature.

4.2. Comparison with Previous Measurements

Despite its importance in our understanding of star formation, the distance to the ONC is quite uncertain. Until recently there has only been one model-independent distance measurement—the marginally significant parallax from *Hipparcos* of the star HD 37061, which corresponds to a distance of 361\(^{+168}_{-87}\) pc (Bertout et al. 1999).

Many authors have estimated the distance to the cluster by fits to the upper main sequence, a procedure that is complicated by systematic uncertainties in the models, the variable background and extinction of the Orion Nebula, and the region over which stars are included in the analysis, among other issues. Some results with this technique are those of Penston (1973), who found a distance of 363\(^{+26}_{-24}\) pc, using IR photometry to characterize each star’s extinction individually; a later, more detailed analysis by Penston et al. (1975), who found ~400 \( \pm 20 \); Warren & Hesser (1978), who found a distance of 483\(^{+51}_{-57}\) pc; and Anthony-Twarog (1982), who reanalyzed the data from Warren & Hesser (1978) and found a distance of 434\(^{+19}_{-21}\) pc. These results alone—some of which make use of the same data, others that use the same techniques—show a spread of more than 100 pc, illustrating the difficulty of such measurements. Many authors have also attempted statistical techniques that combine the proper-motion and radial velocity distributions of the stars with assumptions regarding cluster expansion or contraction. Two early examples of this technique are Strand (1958), who find a distance of 525 pc, and Johnson (1965), who find 380 pc.

Although the *Hipparcos* mission could only marginally detect the parallax of a single star in the ONC, the combination of the astrometric measurements of many stars has yielded some results for Orion. Wilson et al. (2005) analyzed the aggregate astrometric motions of stars foreground and background to the Orion A in three distinct regions of the cloud. They estimate a distance of 465\(^{+75}_{-73}\) pc to the ONC region. This distance is larger than what we measure, but is consistent with our measurement at the 1 \( \sigma \) level. Brown et al. (1994) also used arguments regarding foreground and background stars, but instead comparing their reddening and 100 \( \mu \)m fluxes to estimate distances to the near and far edges of the cloud of 320 and 500 pc.

The orbital parameters of binary systems can be used in some cases to determine very accurate distances. Stassun et al. (2004) have analyzed an eclipsing binary 0.38° south of \( \Theta^1 \) C Ori and found it to be at 419 \( \pm 21 \) pc. However, its status as a member of the ONC is somewhat uncertain because of its relatively old age and location relative to the cluster. The distance to this binary agrees with our distance to the ONC. Recent work by Kraus et al. (2007) on the visual binary system containing \( \Theta^1 \) Ori C yields two equally good orbital solutions that their data cannot yet distinguish. Assuming a luminosity-mass relationship for the stars they find distances of 384 \( \pm 11 \) and 434 \( \pm 12 \) pc from the two orbits. Further astrometric and spectroscopic observations of this system may provide a very accurate distance in the future.

Genzel et al. (1981) combined observations of the proper motions and radial velocities of H\(_2\)O masers in the BN/KL region with the assumption of a spherical, uniformly expanding, thick shell and found a distance of 480 \( \pm 80 \) pc. Because of its relative precision and independence from stellar evolution calculations, this distance has become the canonical distance to the ONC. Indeed, many studies of the ONC population and star formation make use of this distance without consideration of its substantial uncertainties. Our distance measurement is 20\% closer than that of Genzel et al. (1981), although within their combined uncertainties. However, our distance is more precise and does not depend on the assumption of geometries for expanding maser sources, which has been shown to be considerably more complex in many cases than what these authors assume (Greenhill et al. 2005).

Very recently, Hirota et al. (2007) measured the annual parallax of one H\(_2\)O maser spot in the Orion BN/KL outflow using the VLBI Exploration of Radio Astronomy (VERA). The parallax they measure corresponds to a distance of 437 \( \pm 19 \) pc using only the motion in right ascension, and 445 \( \pm 42 \) when they solve for the parallax using both the right ascension and declination. Note that these error bars are only statistical, and the latter value agrees with ours at the 1 \( \sigma \) level. Parallax determinations from maser spot motion can be problematic, because of intrinsic structure changes and/or spot acceleration. For the spot in question Hirota et al. detect changes in its emission-line profile over their 2 years of observation, which likely indicate changes in the structure of the source. Stellar parallax measurements are less vulnerable to this type of systematic uncertainty. If the difference between our VLBA measurement and the Hirota et al. VERA determination is real, and the VERA error bars are accurate, it may argue for a larger separation between the BN/KL region and the ONC along the line of sight.

Finally, we compare our distance to the recent work of Jeffries (2007), who has used the statistical properties of pre-main-sequence star rotation to determine a distance of 392 \( \pm 32 \) pc to the ONC. This techniques involves the assumption of random spin orientations for the stars in the cluster and makes use of a spectral type—effective temperature scale for pre-main-sequence stars. From the whole sample analyzed by Jeffries (2007) a distance of 440 \( \pm 34 \) pc is derived. However, excluding stars that show evidence of accretion—a factor that makes the necessary radius determination unreliable—lowers the distance to 392 \( \pm 32 \) pc. Our distance agrees very well with this latter value. Jeffries (2007) notes that the distance they determine is very sensitive to the assumed spectral type—effective temperature scale, such that distance scales with the square of the effective temperature. In addition, it is clear that the exclusion of classical T Tauri stars, which show evidence for accretion, significantly changes the derived distance, indicating that an accurate account of the various sources of systematic error is extremely important to this technique.

To summarize, we present a distance to the ONC of 389\(^{+24}_{-21}\) pc using the fundamental technique of parallax. In contrast to previous distance estimates, this measurement does not rely on modeling of stellar evolution, cluster dynamics, or calibrations of effective temperature for pre-main-sequence stars. In comparing
our measurement to previous values, we find it to be consistent with many prior measurements within their substantial error bars. We find good agreement with recent values from Jeffries (2007), Kraus et al. (2007), and Stassun et al. (2004), but independent of the various assumptions those authors are forced to make.

4.3. Implications of a Closer Distance to the ONC

Many studies of the Orion Nebula assume the distance of Genzel et al. (1981) or similar. Our distance is 20% closer. In luminosity terms, this change means luminosities are a factor of 1.5 lower than previously claimed, a result that is especially important for the determination of pre-main-sequence star ages, which scale with luminosity as \( t \propto L^{-3/2} \). Therefore, at a distance of 390 pc, the stars are nearly twice as old as they would be at 480 pc. This scaling of age with luminosity is true only for fully convective pre-main-sequence stars that have contracted by a substantial amount from their initial radii (see, for instance, Palla & Stahler [1999] for further discussion). Near the birth line this assumption breaks down and the ages will not be affected to the same degree. A decrease in luminosity will therefore age the entire population of pre-main-sequence stars, but not uniformly, increasing the age spread of the population.

The distribution of stellar ages in Orion is the basis for many theories describing star formation in the region and massive, clustered star formation in general. These theories can be broken down into two general categories—those that purport that star formation in the ONC happened suddenly and quickly (e.g., Hartmann et al. 2001; Hartmann 2003), and those that argue that star formation has been occurring over a longer timescale, but has been accelerating in recent times (e.g., Palla & Stahler 2000; Tan et al. 2006; Huff & Stahler 2006). The age spread of cluster members is a fundamental measurement of the timescale of star formation in the cluster. A larger age spread, as would result from the decrease in luminosity, tends to favor models in which star formation has occurred over a more extended period of time.

Another interesting feature of the stellar population in Orion is that the high-mass stars seem to fall above the expected zero-age main sequence for the cluster (Palla & Stahler 1999; Hillenbrand & Hartmann 1998). Palla & Stahler (1999) argue that this must be due to a systematic problem in determining the luminosities, effective temperatures, or some combination thereof. These analyses assumed a distance of 470 pc, so there is indeed a systematic problem in determining the luminosities of the high-mass stars into much better agreement with the zero-age main sequence predictions.

5. CONCLUSIONS

We have monitored the astrometric motion of the flaring, nonthermal radio star GMR A over the course of 2 years with the Very Long Baseline Array (VLBA). We determine from these data the proper motion and parallax of the star. Based on its young age, its proximity to the center of the Trapezium on the sky, the consistency of its proper motion with that of the cluster, and its location embedded in molecular gas, the probability that GMR A is a member of the Orion Nebula Cluster (ONC) is very high, and thus the distance we determine based on its parallax is representative of the cluster as a whole. We find that the ONC is at a distance of 389\pm24 pc, nearly 100 pc closer than the canonical distance of 480 pc determined by Genzel et al. (1981). The distance presented here is in good agreement with recent work by Jeffries (2007), with the advantage of being independent of assumptions about stellar properties. A closer distance has important implications for the study of star formation in the Orion Nebula, one of the most well-studied sites of massive star formation, most notably the increase in the ages and the age spread of the pre-main-sequence stars in the cluster. The decrease in luminosity also brings the more massive stars into better agreement with the zero-age main sequence.

Further VLBA observations of other radio stars in the ONC may overcome the limitations of a single star distance and begin to probe the depth of the cluster. In addition, suitable targets for this type of observation should be found in most clusters with substantial pre-main-sequence populations. Future VLBI observations of magnetically active, pre-main-sequence stars in these clusters could provide precise, fundamental distance measurements to many nearby star-forming regions.

The authors would like to thank the referee for thorough and helpful comments. We would also like to thank Steve Stahler and Reinhard Genzel for sharing their expertise on the Orion region. K. M. S. acknowledges support from an NSF Graduate Research Fellowship, and would like to thank Franck Marchis and Jason Wright for helpful discussions. The research of J. E. G. P. was is supported in part by NSF grant AST 04-06987. The National Radio Astronomy Observatory is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

Facilities: VLBA

REFERENCES

André, P., Deeney, B. D., Phillips, R. B., & Lestrade, J.-F. 1992, ApJ, 401, 667
Anthony-Twarog, B. J. 1982, AJ, 87, 1213
Baumgardt, H., Dettbarn, C., & Widen, R. 2000, A&AS, 146, 251
Bertout, C., Robinchon, N., & Arenou, F. 1999, A&A, 352, 574
Bower, G. C., Plambeck, R. L., Bolatto, A., McCrady, N., Graham, J. R., de Pater, I., Liu, M. C., & Baganoff, F. K. 2003, ApJ, 598, 1140
Brinks, W. F., Benson, J. M., Goss, W. M., & Thorsett, S. E. 2002, ApJ, 571, 906
Brown, A. G. A., de Geus, E. J., & de Zeeuw, P. T. 1994, A&A, 289, 101
Chatterjee, S., Cordes, J. M., Vlemmings, W. H. T., Arzoumanian, Z., Goss, W. M., & Lazio, T. J. W. 2004, ApJ, 604, 339
Cohen, M., & Kuhl, L. V. 1979, ApJS, 41, 743
Cordes, J. M., & Lazio, T. J. W., 2002, preprint (astro-ph/0207156)
Feigelson, E. D., Broos, P., Gauffre, J. A., III, Garmire, G., Hillenbrand, L. A., Pravdo, S. H., Townsley, L., & Tsiboi, Y. 2002, ApJ, 574, 258
Felli, M., Churchwell, E., Wilson, T. L., & Taylor, G. B. 1993a, A&AS, 98, 137
Felli, M., Taylor, G. B., Catarzi, M., Churchwell, E., & Kurtz, S. 1993b, A&AS, 101, 127
Fomalont, E. B. 2005, in ASP Conf. Ser. 340, Future Directions in High Resolution Astronomy, ed. J. Romney & M. Reid (San Francisco: ASP), 460
Garay, G., Moran, J. M., & Reid, M. J. 1987, ApJ, 314, 535
Genzel, R., Reid, M. J., Moran, J. M., & Downes, D. 1981, ApJ, 244, 884
Genzel, R., & Stutzki, J. 1989, ARA&A, 27, 41
Getman, K. V., Feigelson, E. D., Garmire, G., Murray, S. S., & Hamden, F. R., Jr. 2003, IAU Circ., 8068, 2
Gomez, L., Rodriguez, L. F., Loinard, L., Lizano, S., Poveda, A., & Allen, C. 2005, ApJ, 635, 1160
Gomez, L., Rodriguez, L. F., Loinard, L., Lizano, S., Poveda, A., & Allen, C. 2005, ApJ, 635, 1160
Greenhill, L. J., Chandler, C. J., Reid, M. J., & Humphreys, E. M. L. 2005, in Protostars and Planets V, ed. V. Mannings et al. ( Houston: LPI ), 8614
Hartkopf, W. I., McAlister, H. A., & Franz, O. G. 1989, AJ, 98, 1014
Hartmann, L. 2003, ApJ, 585, 398
Hartmann, L., Balles, Y.-V. Paredes, J., & Bergin, E. A. 2001, ApJ, 562, 852
Hillenbrand, L. A., & Hartmann, L. W. 1998, ApJ, 492, 540
Hirotê, T., et al. 2007, PASJ, 59, in press (arXiv: 0705.3792v1)
Huff, E. M., & Stahler, S. W. 2006, ApJ, 644, 355
Hirota, T., et al. 2007, PASJ, 59, in press (arXiv: 0705.3792v1)
Huff, E. M., & Stahler, S. W. 2006, ApJ, 644, 355
Hirota, T., et al. 2007, PASJ, 59, in press (arXiv: 0705.3792v1)
