1. INTRODUCTION

Newborn multiple stars and small stellar clusters tend to be dynamically unstable. In these systems, close encounters can lead to the acceleration of one or more of the members, which—when the acceleration is sufficient—can escape their birthplace and become runaway stars. If they affect stars that have not yet completed their formation, strong dynamical interactions may be expected to seriously modify the outcome of the star-forming process. If they were sufficiently common, they could even be partly responsible for the overall shape of the initial mass function (Reipurth 2000).

As one of the nearest sites of profuse star formation, Orion is an obvious candidate to search for signs of strong dynamical interactions. Indeed, one of the most promising examples of a runaway star is located there: the Becklin-Neugebauer (BN) object (Becklin & Neugebauer 1967). The runaway nature of BN was demonstrated by Plambeck et al. (1995), who used multiepoch radio observations to show that it moved at a projected velocity of about 50 km s$^{-1}$ toward the northeast, relative to a nearby radio source taken as a reference point. Tan (2004) then proposed that it had escaped from the Trapezium about 4000 years ago as a result of a dynamical interaction with the other members of this multiple system. However, Rodriguez et al. (2005) recently showed that another source (the radio source I; Churchwell et al. 1987), located much closer to BN than the Trapezium, is quickly moving away from BN. Since the velocities of BN and I are almost exactly antiparallel, Rodriguez et al. (2005) suggested that these two sources were originally members of a common system that disintegrated about 500 years ago.

The proper motions reported by Rodriguez et al. (2005) were calibrated against distant quasars and can therefore be considered absolute. However, because of the differential rotation of the Galaxy, Orion is expected to move relatively to these distant quasars, and one would ideally want to register all motions to the rest frame of Orion rather than use absolute values. In the present article, we reanalyze multiepoch wide-field Very Large Array (VLA) observations of Orion to determine the mean absolute motion of Orion. This allows us to show that yet another source in the KL region (the radio counterpart of the infrared source n) can be considered a runaway and to propose that the BN object, the radio source I, and the infrared source n were all initially members of a common multiple system.

2. OBSERVATIONS

The high-frequency (22 and 43 GHz) data used by Rodriguez et al. (2005) have a limited field of view and properly sample only the KL/BN region where a mere handful of radio sources are detected. To measure the mean absolute proper motion of Orion, one must turn to lower frequency observations that provide a larger effective field of view (several arcminutes) and encompass the Trapezium, BN/KL, and their surroundings. Thus, we searched the VLA archive for 3.6 and 6 cm observations of Orion taken in the most extended (A) configuration of the array—the latter requirement ensures that only data with the highest angular resolution were selected. Four data sets were retrieved, which span a total of 15 yr, with a typical step of 5 yr (Table 1).

The data were calibrated in AIPS following standard procedures, and the calibrated visibilities were imaged using weights intermediate between natural and uniform (with the ROBUST parameter set to 0). To obtain accurate absolute astrometry, we precessed the data taken in B1950.0 to J2000.0 using the task UVFIX and used the most recent position of the phase calibrators for all epochs. With this prescription, we expect the residual systematic error affecting our data to be at most a few milliarcseconds (mas). Self-calibration was applied to improve the dynamical
range of the images and to allow the detection of fainter sources. To estimate the effect of the self-calibration process on our final astrometry, we compared the position of the 15 brightest sources before and after self-calibration. Only small, random shifts (2–3 mas) were found. These small shifts, as well as the small possible residual errors due to the uncertainties on the positions of the phase calibrators mentioned above, were formally taken into account by adding in quadrature a systematic error of 10 mas to the positional uncertainty delivered by the Gaussian fitting program (see §3.1).

### 3. RESULTS

#### 3.1. Mean Proper Motion and Velocity Dispersion of Orion

In total, 35 sources were detected in at least three of our four epochs (Fig. 1a; Tables 1 and 2). The position of each source at each epoch was determined using a linearized least-squares fit to a Gaussian ellipsoid function (task `imfit` of AIPS). The final positional error assigned to each observation is the quadratic sum of the relative error of the source in the given image (proportional to the angular resolution over the signal-to-noise ratio) and a systematic error of 10 mas (see §2). Nearly all of our sources are very compact (<0.5; Table 2), so we do not expect source structure to significantly affect our astrometry.

The source proper motions were then obtained by adjusting their displacements over the celestial sphere with a linear fit (Table 3). To obtain the mean absolute proper motion of Orion, we finally computed the weighted average of these individual measurements, obtaining

\[
\begin{align*}
\mu_a \cos \delta &= +0.8 \pm 0.2 \text{ mas yr}^{-1}, \\
\mu_b &= -2.3 \pm 0.2 \text{ mas yr}^{-1}.
\end{align*}
\]

Transformation of these values to the Galactic coordinate system yields

\[
\begin{align*}
\mu_l \cos b &= +2.1 \pm 0.2 \text{ mas yr}^{-1}, \\
\mu_b &= -0.1 \pm 0.2 \text{ mas yr}^{-1}.
\end{align*}
\]

It is interesting to compare these observational values with those expected from the differential rotation of the Galaxy. The proper motions determined with the VLA are measured with respect to the Sun. To obtain the corresponding values expected theoretically, we adopt a model for the local rotation of the Galaxy where the Oort constants are \( A = 14.4 \) and \( B = -12.0 \text{ km s}^{-1} \text{ kpc}^{-1} \) (Allen 2000) and where the distance from the Sun to the Galactic center is \( R_0 = 8.5 \text{ kpc} \). For the peculiar motion of the Sun (required to transform the barycentric coordinates provided by the VLA to values relative to the local standard of rest [LSR]), we use \( U_\odot = +9.0, V_\odot = +12.0, \) and \( W_\odot = +7.0 \text{ km s}^{-1} \) (Allen...
Here, we follow the traditional convention where $U$ runs from the Sun to the Galactic center, $V$ is in the Galactic plane, perpendicular to $U$ and positive in the direction of Galactic rotation, and $W$ is perpendicular to the Galactic plane, positive toward the Galactic north pole. Finally, we use the distance estimate to Orion obtained by Genzel et al. (1981) applying the expanding cluster parallax method to a group of H$_2$O masers, $d = 480 \pm 80$ pc. Using these values, and assuming that Orion is at rest with respect to its LSR, we expect the proper motion of Orion relative to the Sun to be

$$\mu_U \cos b = +1.9 \pm 0.4 \text{ mas yr}^{-1},$$

$$\mu_V = -0.2 \pm 0.2 \text{ mas yr}^{-1}.$$ 

Here, the error bars account for the uncertainty on the distance. The agreement between the expected values and the measured one is—quite remarkably—better than 0.2 mas yr$^{-1}$, showing that Orion is indeed nearly at rest with respect to its LSR. An interesting consequence of this result is that, in spite of its location nearly 150 pc below the Galactic plane, Orion shows very little vertical motion relative to it.

Also using the individual proper motions, we can estimate the velocity dispersion of the radio sources cluster:

$$\sigma_U = 2.3 \pm 0.2 \text{ mas yr}^{-1} \equiv 5.2 \pm 0.5 \text{ km s}^{-1},$$

$$\sigma_V = 3.1 \pm 0.2 \text{ mas yr}^{-1} \equiv 7.1 \pm 0.5 \text{ km s}^{-1}.$$ 

The error bars quoted here on the velocity dispersion do not include the effects of the uncertainty on the distance to Orion—which would typically contribute an extra 1 km s$^{-1}$ to the errors. The reason for omitting this contribution is because we will momentarily compare the radio and optical velocity dispersions that would be equally affected by a systematic error on the distance. The values obtained here for the velocity dispersion are fairly large and imply a three-dimensional velocity dispersion in excess of 10 km s$^{-1}$. Finally, we should point out that—except in the KL region (see § 3.3)—the residual velocities do not define an organized pattern (of expansion, streaming motions, or infall), but appear to be random.

### 3.2. Comparisons with Optical Results

It is interesting to compare the results found here with those obtained at optical wavelengths. For that purpose, we use the

#### Table 2

**General Properties of the Radio Sources**

| Source Number | Other Name | $\alpha_{2000.0}$ | $\delta_{2000.0}$ | Flux Density (mJy) | Size (arcsec) |
|---------------|------------|-----------------|-----------------|-------------------|--------------|
| 1..............| GMR A      | 05 35 11.8022   | -05 21 49.229   | 12.2              | <0.1         |
| 2..............| BN object  | 05 35 14.1131   | -05 22 22.793   | 3.8               | <0.1         |
| 3..............| GMR C      | 05 35 14.1614   | -05 23 01.129   | 6.7               | 0.7          |
| 4..............| IR n       | 05 35 14.3553   | -05 22 32.702   | 1.6               | 0.6          |
| 5..............| GMR 1      | 05 35 14.5121   | -05 22 30.521   | 0.7               | <0.1         |
| 6..............| GMR D      | 05 35 14.8969   | -05 22 25.394   | 4.1               | <0.1         |
| 7..............| GMR 14     | 05 35 15.5226   | -05 23 37.375   | 4.9               | 0.4          |
| 8..............| GMR 26     | 05 35 15.7288   | -05 23 22.477   | 3.1               | 0.2          |
| 9..............| GMR 13     | 05 35 15.7964   | -05 23 26.562   | 11.3              | 0.3          |
| 10.............| GMR 12     | 05 35 15.8243   | -05 23 14.123   | 28.1              | <0.1         |
| 11.............| GMR 11     | 05 35 15.8393   | -05 23 22.480   | 11.5              | 0.2          |
| 12.............| GMR 10     | 05 35 15.8488   | -05 23 25.540   | 6.2               | 0.3          |
| 13.............| GMR 24     | 05 35 15.9015   | -05 23 37.970   | 2.3               | <0.1         |
| 14.............| GMR 9      | 05 35 15.9508   | -05 23 49.801   | 9.9               | 0.5          |
| 15.............| Zapata 46  | 05 35 15.9971   | -05 23 52.940   | 2.3               | 0.3          |
| 16.............| GMR 8      | 05 35 16.0674   | -05 23 24.333   | 5.7               | <0.1         |
| 17.............| GMR 15     | 05 35 16.0716   | -05 23 07.073   | 5.1               | 0.2          |
| 18.............| GMR 22     | 05 35 16.0776   | -05 23 27.826   | 1.9               | <0.1         |
| 19.............| GMR 7      | 05 35 16.2890   | -05 23 16.575   | 10.8              | 0.2          |
| 20.............| GMR 16     | 05 35 16.3269   | -05 23 22.597   | 3.7               | <0.1         |
| 21.............| GMR K      | 05 35 16.3986   | -05 22 35.315   | 1.4               | 0.2          |
| 22.............| GMR 21     | 05 35 16.6190   | -05 23 16.096   | 1.9               | <0.1         |
| 23.............| GMR 6      | 05 35 16.7527   | -05 23 16.452   | 25.0              | 0.2          |
| 24.............| GMR 17     | 05 35 16.7694   | -05 23 28.036   | 3.9               | <0.1         |
| 25.............| GMR 5      | 05 35 16.8466   | -05 23 26.202   | 18.5              | 0.4          |
| 26.............| GMR E      | 05 35 16.9716   | -05 22 48.677   | 2.8               | 0.4          |
| 27.............| GMR 4      | 05 35 16.9796   | -05 23 36.984   | 9.5               | 0.3          |
| 28.............| GMR 3      | 05 35 17.0665   | -05 23 34.027   | 4.3               | <0.1         |
| 29.............| GMR L      | 05 35 17.3514   | -05 22 35.897   | 2.4               | 0.4          |
| 30.............| GMR 2      | 05 35 17.5605   | -05 23 24.863   | 5.0               | 0.2          |
| 31.............| GMR 1      | 05 35 17.6739   | -05 23 40.908   | 9.7               | 0.5          |
| 32.............| GMR G      | 05 35 17.9489   | -05 22 45.468   | 3.4               | <0.1         |
| 33.............| GMR 19     | 05 35 18.0447   | -05 23 30.719   | 4.6               | 0.2          |
| 34.............| Zapata 75  | 05 35 18.2422   | -05 23 15.617   | 0.7               | <0.1         |
| 35.............| GMR F      | 05 35 18.3706   | -05 22 37.436   | 3.0               | <0.1         |
studies of Jones & Walker (1988, hereafter JW88) and van Altena et al. (1988, hereafter vA88). There are about a dozen sources in common between the catalog of JW88 and the present list of 35 radio sources, and three sources in common between our radio data and the list of vA88. For the latter three sources, the radio and optical measurements agree very well: to within 1σ. We find similarly good agreement with the sources of JW88 that have modest optical proper motions. However, there are a few sources for which JW88 measured large proper motions, whereas we find only small ones. Interestingly, Tian et al. (1996) also noted that their own optical-proper-motion measurements in Orion agreed well with those of JW88 only for sources with proper motions smaller than 0.6 mas yr\(^{-1}\). Thus, the few sources with large proper motions in the catalog of JW88 might be less trustworthy than the others, and we consider that our radio measurements agree overall very well with published optical ones.

The velocity dispersion for optical measurements is best obtained from the catalog of JW88, which contains over 1000 sources. Applying the same weighted average technique used for the radio data, and restricting ourselves to objects with high membership probability, we obtain the following velocity dispersions for the optical measurements:

\[
\sigma_\alpha = 1.04 \pm 0.02 \text{ mas yr}^{-1} \equiv 2.37 \pm 0.04 \text{ km s}^{-1},
\]

\[
\sigma_\varpi = 1.24 \pm 0.02 \text{ mas yr}^{-1} \equiv 2.83 \pm 0.04 \text{ km s}^{-1}.
\]

It is noteworthy that the optical dispersion is about 2.5 times smaller than that obtained with the radio data. This is unlikely to be a consequence of underestimating the errors associated with the radio measurements given the remarkable agreement between the average absolute proper motion of Orion measured at radio wavelengths and the theoretical expectation (§ 3.1) and the good agreement between the radio and optical proper motions for sources where both were measured. To reinforce this last point, it should be noted that when there was a significant disagreement between the radio and optical measurements, the radio observations gave smaller proper motions. If they played a role, these discrepancies would therefore tend to make the radio velocity dispersion smaller than the optical one, rather than the opposite.
It is plausible that the radio observations are biased toward a certain subset of objects with peculiar kinematics. Indeed, it is well known that low-mass young stars tend to be bright at radio wavelengths. Consequently, a large fraction of our sample of radio sources are likely to be T Tauri stars, whereas the optical observations tend to be biased toward brighter (i.e., less embedded and more massive) stars. The present difference between the velocity dispersion obtained from optical and radio observations would then suggest that lower mass and/or younger sources have larger random velocities than their older and/or more massive counterparts.

3.3. Fast-moving Sources

Having measured the mean absolute proper motion of Orion, we are now in a position to register the motion of all of our sources in the Orion rest frame. Interestingly, only two sources of the Trapezium cluster appear to show peculiar residual kinematics: GMR 14 (Garay et al. 1987) and source 46 in the list of Zapata et al. (2004). GMR 14 is an extended radio source associated with a proplyd reported by O’Dell & Wen (1994). Consequently, the detection of an apparent motion for this source must

![Fig. 2.—Comparison between the positions of the sources BN, I, and n at the first and last of our observations. In each panel, the cross shows the center position of the sources at the first epoch. The first contours and the contour spacings are 0.2 mJy beam$^{-1}$ for sources I and n, and 0.5 mJy beam$^{-1}$ for BN.](image)
be taken with caution, since internal variability could easily produce changes in the centroid position even in the absence of a true displacement. As for source 46 in the list of Zapata et al. (2004), it is highly time variable and located near GMR 23 (at only 0\".6), which is also a variable radio source. In such a configuration, differential variability could again easily produce centroid shifts mimicking position changes, and the present detection of a large proper motion must be considered very cautiously. Thus, we consider that the detection of large residual proper motions for two sources in the Trapezium must be further investigated before being accepted as fully trustworthy.

The situation is quite different in the BN/KL region, where three of the four detected sources are found to have residual proper motions above 4 \sigma (Fig. 2; Table 3). For sources BN and I, we first confirm the original finding by Rodrı́guez et al. (2005) that these two sources are moving away from one another. But the present determination of the mean absolute proper motion of Orion further shows that neither source is at rest with respect to Orion. In the Orion rest frame, BN is moving toward the southeast at 15 km s\(^{-1}\) (Table 3). Since the present proper motions for sources BN and I are compatible with, but less precise than, those reported by Rodrı́guez et al. (2005), we use the values reported by those authors—but corrected for the overall motion of Orion measured here—in the rest of this paper. In addition to the confirmation of the large motions of BN and I, we report here for the first time that the radio counterpart of the infrared source n also has a very large residual velocity, 24 km s\(^{-1}\) approximately toward the south. It should be pointed out that although n was contained in the field of view studied by Rodrı́guez et al. (2005), it was not included in their analysis because it is faint and not detected at high frequencies. The infrared source n (Lonsdale et al. 1982) was proposed to be a young embedded member either of the KL region or of the Trapezium (Lonsdale et al. 1982; Wynn-Williams et al. 1984; Dougados et al. 1993).

4. DISCUSSION

The present results show that there are three sources moving at projected velocities of 15–25 km s\(^{-1}\) within a region only about 10\" (0.02 pc) across, centered near the BN object, a situation that is very unlikely to be coincidental. To investigate the possible origin of these motions, it is useful to reconstruct the past positions of the three fast-moving radio sources using their present locations and velocities—assuming that the latter have remained constant. Interestingly, it is found that about 500 years ago, all three sources were—at least in projection—within a few arcseconds of each other (Fig. 3). Rodrı́guez et al. (2005) had already noted that the velocities of BN and I were almost exactly antiparallel and argued that these two sources were originally members of a common system that disintegrated about 500 years ago. The present finding that the double radio source associated with n is also quickly moving away from the position where Rodrı́guez et al. (2005) placed the parental system lends further support to their interpretation and suggests that the original multiple system disintegrated in at least three pieces. An objection that could be made to this interpretation is the fact that the total momentum of the three sources does not seem to be 0 when measured in the Orion rest frame. That objection is not very strong, however, since (1) the parental system could easily have had a residual motion relative to the Orion rest frame of a few mas yr\(^{-1}\), and (2) the existence of other sources (invisible at centimeter wavelengths) moving away in different directions cannot be ruled out. It is also possible that source n is a low-mass object with a relatively small linear momentum. In that case, the only two important contributions are those of BN and I, whose proper motions average to 0 within the errors.

As discussed at length by Rodrı́guez et al. (2005), in this disintegration scheme, the current (positive) kinetic energy of the escaping sources BN, I, and n must have been taken from the total energy of the parental multiple system. Since the latter is assumed to have been originally bound, its total energy must have been negative. Conservation of the total energy then dictates that, to compensate for the excess of kinetic energy carried by BN, I, and n, some components must have seen their energy become more negative, so they must be more bound than they originally were. In the classical case of the disintegration of a nonhierarchical triple system, one of the objects escapes at high speed, while the other two are rearranged into a tight binary. The final total energy of these two bodies is more negative than it was before the ejection, and the excess of positive energy thus liberated is carried away by the escaping star. The simplest generalization to the case of the BN/KL region is that sources BN, I, and n must have been initially part of a tight group, which disintegrated about 500 years ago as a result of a strong dynamical interaction as in the n-body simulations of Poveda et al. (1967). Because of the interaction, BN, I, and n acquired a large total kinetic energy (about 2 \times 10^{47} ergs if both BN and n are 10 M\(_{\odot}\) stars, while source I is a 20 M\(_{\odot}\) star), and one or more tight binaries were formed.

A related interpretation follows from the recent reanalysis by Bally & Zinnecker (2005) of the origin of the massive outflow originating near sources I and n (Allen & Burton 1993). This outflow is associated with gaseous fingers tracing strong bow shocks and has traditionally been interpreted as the result of a
powerful explosion (e.g., Allen & Burton 1993; Schultz et al. 1999; Bally & Zinnecker 2005). The analysis of the proper motions of the fingers indicates that the explosion must have occurred less than a thousand years ago—a value of 1000 yr is obtained if the velocities have remained constant, but the actual time elapsed since the explosion may be somewhat less if there was significant deceleration. Bally & Zinnecker (2005) proposed that the explosion may have happened when source I (a 20 $M_\odot$ star) swallowed a relatively low-mass (1 $M_\odot$) object. Indeed, the total energy liberated by such a merger is about $3 \times 10^{48}$ ergs, well in excess of the total energy carried by the outflow ($4 \times 10^{47}$ ergs; Kwan & Scoville 1976). Bally & Zinnecker (2005) also noted that the epoch of the explosion coincides roughly with the time when BN and I were very near to each other and argued that this was unlikely to be a coincidence. Consequently, they favored a scenario in which the BN object was ejected from I about 500 years ago, in the same dramatic event that produced the massive outflow.

The present data suggest that tight binaries have formed as a result of strong dynamical interactions within a multiple system, but they do not give any information about the ultimate fate of these tight binaries, i.e., whether or not a merger subsequently occurred. As an alternative to a merger, we note that rapid accretion of a disrupted 1 $M_\odot$ disk around one of the massive stars during the close dynamical interaction that lead to the decay would provide a sufficient amount of energy to power the large $H_2$ outflow. This scenario could explain the near simultaneity of the dynamical decay and of the explosion that produced the flow with no need for a merger.

5. CONCLUSIONS

In the present paper, we have measured the absolute proper motion of Orion relative to the Sun using multiepoch radio observations. The value we obtain agrees remarkably well with that expected theoretically from the local rotation of the Milky Way. Using this new piece of information, we then showed that three of the four radio sources in the Orion KL region have large residual velocities. All three sources appear to move away from a common point of origin, where we argue that a parental—now defunct—multiple system must have been located. As proposed by Bally & Zinnecker (2005), the decay of this original system may be related to the massive $H_2$ flow centered near Orion KL.

The velocity dispersion of the Orion cluster of radio sources appears to be nearly 3 times larger than the velocity dispersion of the optical stars, suggesting that there is a systematic difference between the kinematics of the objects detected at optical and radio wavelengths. It is plausible that this difference is related to the age or the mass of the stars preferentially traced by each wavelength.

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