MONITORING THE LARGE PROPER MOTIONS OF RADIO SOURCES IN THE ORION BN/KL REGION

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ABSTRACT

We present absolute astrometry of four radio sources in the Becklin-Neugebauer/Kleinman-Low (BN/KL) region, derived from archival data (taken in 1991, 1995, and 2000) as well as from new observations (taken in 2006). All data consist of 3.6 cm continuum emission and were taken with the Very Large Array in its highest angular resolution A configuration. We confirm the large proper motions of the BN object, the radio source I (GMR I), and the radio counterpart of the infrared source n (Orion-n), with values from 15 to 26 km s⁻¹. The three sources are receding from a point between them from where they seem to have been ejected about 500 years ago, probably via the disintegration of a multiple stellar system. We present simulations of very compact stellar groups that provide a plausible dynamical scenario for the observations. The radio source Orion-n appeared as a double in the first three epochs, but as single in 2006. We discuss this morphological change. The fourth source in the region, GMR D, shows no statistically significant proper motions. We also present new, accurate relative astrometry between BN and radio source I that restrict possible dynamical scenarios for the region. During the 2006 observations, the radio source GMR A, located about 1' to the northwest of the BN/KL region, exhibited an increase in its flux density of a factor of ~3.5 over a timescale of 1 hr. This rapid variability at centimeter wavelengths is similar to that previously found during a flare at millimeter wavelengths that took place in 2003.

Subject headings: astrometry — ISM: individual (Orion) — radio continuum: stars — stars: flare — stars: pre-main-sequence

1. INTRODUCTION

The Orion BN/KL region is at the center of a remarkable, fast (30–100 km s⁻¹), and massive (~10 M☉) outflow, with a kinetic energy of order 4 × 10⁴⁷ ergs, which Kwan & Scoville (1976) ascribe to an explosive event and which also manifests itself as shock-excited molecular hydrogen (H₂) emission at near-infrared wavelengths (Beckwith et al. 1978). Observations with higher angular resolution showed that this molecular outflow is bipolar and weakly collimated, with its blueshifted lobe toward the northwest and its redshifted lobe to the southeast (Erickson et al. 1982; Rodríguez-Franco et al. 1999). This outflow was later resolved into “fingers” of H₂ emission, most probably tracing shocked gas, that point away from the BN/KL region to the northwest and southeast (Allen & Burton 1993; Stolovy et al. 1998; Schultz et al. 1999; Salas et al. 1999; Kaifu et al. 2000). These observations indicate that a powerful ejection occurred in the BN/KL region recently. The H₂ “finger” system consists of over 100 individual bow shocks, which delineate a wide-angle bipolar outflow along a position angle of about 135°. The proper motions of the H₂ knots suggest that the explosion took place less than about 1000 yr ago (Lee & Burton 2000; Doi et al. 2002; Nissen et al. 2007).

The cause of this remarkable outflow remains unknown. Recently, Rodríguez et al. (2005) and Gómez et al. (2005) reported large proper motions (equivalent to velocities of the order of a few tens of km s⁻¹) for the radio sources associated with the infrared sources BN (the “Becklin-Neugebauer object”) and n, as well as for the radio source I. All three objects are located at the core of the BN/KL region and appear to be moving away from a common center where they must all have been located about 500 yr ago. This suggests that all three sources were originally part of a multiple massive stellar system that recently disintegrated as a result of a close dynamical interaction. Bally & Zinnecker (2005) have suggested that, given the uncertainty in the age of the explosion traced by the high-velocity gas that could have experienced deceleration, this phenomenon could have taken place simultaneously with the close dynamical interaction possibly traced by the proper motions of the three radio sources. However, a detailed model that connects the two events is still lacking.

In this paper we report new radio observations of the BN/KL region that monitor and confirm the previously reported large proper motions of sources BN, I, and n. In particular, we present very accurate relative astrometry between the sources BN and I that restricts the past history of the motions of these sources.
We also report the flux variability of objects in the zone. Finally, we propose a dynamical scenario that accounts for the observed high velocity of the stellar objects.

2. OBSERVATIONS AND DATA REDUCTION

We have used 3.6 cm data from the VLA in its most extended A configuration to measure the proper motions of radio sources in the Orion BN/KL region. Observations of this region were available in the VLA archives for 1991 September 6, 1995 July 22, and 2000 November 13. We obtained new observations on 2006 May 12.

The data were analyzed in the standard manner using the AIPS package, and the calibrated visibilities were imaged using weights intermediate between natural and uniform (with the ROBUST parameter set to 0). The data were also self-calibrated in phase and amplitude for each epoch. To diminish the effects of extended emission, we used only visibilities with baselines larger than 2\(\lambda\).

The VLA observations for 1995, 2000, and 2006 were all made with the same phase calibrator, 0541-056 (located at only 1.6\(^\circ\) from the core of Orion), and this provides very reliable absolute astrometry. In contrast, the observations made on 1991 September 6 used as phase calibrator the source 0501-019 (located at 9.1\(^\circ\) from the core of Orion). The astrometric error grows with the angular separation between the phase calibrator and the source (e.g., Pradel et al. 2006). To improve the astrometry of the 1991 image, we used the 2000 positions of nine bright and compact radio sources in the core of the Trapezium region, with no significant proper motions in the study of Gómez et al. (2005) to compare with the positions in the 1991 image. The average shift of the 2000 epoch positions with respect to the 1991 epoch positions is \(\Delta\alpha = -0.0007^\circ \pm 0.0009^\circ\) and \(\Delta\delta = -0.035'' \pm 0.011''\). The shift in right ascension is not statistically significant but we do find a systematic shift in declination between the two epochs, implying that the 1991 declinations should be corrected by \(\Delta\delta = -0.035''\).

3. RESULTS

We have used these multiepoch VLA observations taken over 15 yr (1991–2006) to study the proper motions of the four persistent and compact radio sources clearly detectable in the BN/KL region (Tables 1 and 2 and Figs. 1 and 2). The positions of the sources at each epoch were determined using a linearized least-squares fit to a Gaussian ellipsoid function (task JMFIT of AIPS).

The source proper motions were then obtained by adjusting their displacements over the celestial sphere with a linear fit (Table 2). The proper motions of all four sources are consistent within 1\(\sigma\) with the results of Gómez et al. (2005). At a distance of 414 pc (Menten et al. 2007), 1 mas yr\(^{-1}\) is equivalent to 2.0 km s\(^{-1}\) and the proper motions of BN, I, and n are in the range of 15–26 km s\(^{-1}\). We have thus confirmed the large proper motions of the radio sources I, BN, and Orion-n found by Rodríguez et al. (2005) and Gómez et al. (2005). The fourth source in the region, GMR D (Garay et al. 1987), shows no statistically significant proper motions. During the 2006 observations we detected a transient radio source associated with the Orion G7 star Parenago 1839 (labeled in Fig. 2), that was not detected in the three previous epochs and for which we cannot derive a proper motion. The absolute proper motions of these sources are shown in Figure 2, after being corrected for the mean absolute proper motions of 35 radio sources located in a region with a radius of about 0.1 pc centered at the core of Orion (Gómez et al. 2005), \(\mu_\alpha\cos\delta = +0.8 \pm 0.2\) mas yr\(^{-1}\); \(\mu_\delta = -2.3 \pm 0.2\) mas yr\(^{-1}\). Sandstrom et al. (2007) have noted that the mean absolute proper motions of these 35 radio sources differ at the 1–2 mas yr\(^{-1}\) level from those given by Kharchenko et al. (2005) from astrometry (made also with respect to the frame of remote quasars) of 12 optical stars in the Orion cluster distributed over a region with radius of 0.4 pc, \(\mu_\alpha\cos\delta = +1.96 \pm 0.31\) mas yr\(^{-1}\); \(\mu_\delta = -0.77 \pm 0.46\) mas yr\(^{-1}\). At present it is unclear if these noncoincident values are due to a real difference in the mean absolute proper motions of the two populations of objects studied by Gómez et al. (2005) and by Kharchenko et al. (2005), or to another cause. We have used the values of Gómez et al. (2005) that appear more appropriate for embedded radio sources in Orion.

4. A DYNAMICAL SCENARIO FOR THE REGION

The mass of BN is estimated to be 8 \(M_\odot < M_{\text{BN}} < 12.6 M_\odot\) (Scoville et al. 1983; Rodríguez et al. 2005). Since source \(n\) is moving with the largest proper motion, for simplicity we assume

### Table 1

| Source        | Position \(\alpha (J2000.0)\) | Position \(\delta (J2000.0)\) | Total Flux Density (mJy) | Deconvolved Angular Size \(<\)0.20'' |
|---------------|-------------------------------|-------------------------------|--------------------------|--------------------------------------|
| BN object     | 05 35 14.1099                 | -05 22 22.741                | 4.8 \pm 0.1              | 0.17'' \pm 0.01'' \times 0.08'' \pm 0.03''; +63'' \pm 7'' |
| Orion-n       | 05 35 14.3546                 | -05 22 32.776                | 2.2 \pm 0.2              | 0.50'' \pm 0.04'' \times 0.09'' \pm 20'' \pm 3'' |
| GMR I         | 05 35 14.5141                 | -05 22 30.556                | 1.2 \pm 0.1              | 0.19'' \pm 0.05'' \times 0.15'' \pm 136'' \pm 23'' |
| GMR D         | 05 35 14.8963                 | -05 22 25.390                | 0.7 \pm 0.1              | \leq 0.20'' |

Note.—The positions, flux densities, and deconvolved sizes reported here are from the 2006 May 12 observations.

\(a\) Units of right ascension are hours, minutes, and seconds and units of declination are degrees, arcminutes, and arcseconds. Positional accuracy is estimated to be \(<0.01''\).

\(b\) Major axis \times minor axis; position angle of major axis.

### Table 2

| Source        | \(\mu_\alpha\cos\delta\) (mas yr\(^{-1}\)) | \(\mu_\delta\) (mas yr\(^{-1}\)) | \(\mu_\text{tot}\) (mas yr\(^{-1}\)) | P.A. (deg) |
|---------------|------------------------------------------|--------------------------------|--------------------------------|-----------|
| BN object     | -5.3 \pm 0.9                             | 9.4 \pm 1.1                   | 10.8 \pm 1.0                   | -29 \pm 5 |
| Orion-n       | 0.0 \pm 0.9                              | -13.0 \pm 1.2                 | 13.0 \pm 1.2                   | 180 \pm 4 |
| GMR I         | 4.5 \pm 1.2                              | -5.7 \pm 1.3                  | 7.3 \pm 1.2                    | 142 \pm 10 |
| GMR D         | -0.4 \pm 1.3                             | -1.8 \pm 1.6                  | 1.8 \pm 1.6                    | -166 \pm 42 |

Note.—The errors quoted in this Table are 1\(\sigma\). At a distance of 414 pc (Menten et al. 2007), 1 mas yr\(^{-1}\) is equivalent to 2.0 km s\(^{-1}\).

\(a\) See text for the proper motions reported here.
Fig. 1.— Proper motions for the four persistent radio sources in the Orion BN/KL region. The solid lines are the least-squares fits to the data. The proper motions of source Orion-n are described in the text.
that it has a smaller mass than sources BN and I and neglect its contribution in the conservation of linear momentum and energy. Using the observed proper motions in Table 2, conservation of linear momentum along the direction of motion of BN implies that the mass of source I is \( M_I \approx 1.5 M_{BN} \), i.e., \( 12 M_\odot < M_I < 19 M_\odot \). We identify source I with a close binary formed by dynamical interactions that has the negative binding energy of \( 1 \times 10^{47} \) ergs. To accelerate these objects to their observed total velocities corrected for the radial velocities of each source (Gómez et al. 2005), the dashed angles indicate the error in the position angles of the proper motions. At a distance of 414 pc (Menten et al. 2002), 1 mas yr\(^{-1}\) is equivalent to 2.0 km s\(^{-1}\).

Fig. 2.—VLA contour image at 8.46 GHz toward the Orion BN/KL region for epoch 2006.36. The first contour is 300 \( \mu \)Jy beam\(^{-1}\) and increments are in units of 150 \( \mu \)Jy beam\(^{-1}\). The angular resolution of the image is \( 0.26'' \times 0.22'' \). The individual radio sources are identified. The arrows indicate the direction and proper motion displacement for 200 yr, in the rest frame of the Orion radio sources (Gómez et al. 2005). The dashed angles indicate the error in the position angles of the proper motions.

that it has a smaller mass than sources BN and I and neglect its contribution in the conservation of linear momentum and energy. Using the observed proper motions in Table 2, conservation of linear momentum along the direction of motion of BN implies that the mass of source I is \( M_I \approx 1.5 M_{BN} \), i.e., \( 12 M_\odot < M_I < 19 M_\odot \). We identify source I with a close binary formed by dynamical interactions that has the negative binding energy of \( 1 \times 10^{47} \) ergs. To accelerate these objects to their observed total velocities corrected for the radial velocities of each source (Gómez et al. 2005), the dashed angles indicate the error in the position angles of the proper motions. At a distance of 414 pc (Menten et al. 2002), 1 mas yr\(^{-1}\) is equivalent to 2.0 km s\(^{-1}\).

The required stellar density is thus \( 1.6 \times 10^8 \) stars pc\(^{-3}\), which appears to be very large, since the largest stellar densities found observationally in the Galaxy on scales of \( 0.01-0.1 \) pc are in the range \( (1-4) \times 10^5 \) stars pc\(^{-3}\) (Figuer et al. 2002; Megeath et al. 2005; Beuther et al. 2007). However, in our case we are dealing with much smaller physical scales, of order 0.001 pc, and there is at least one observational example of a very young stellar system where the required stellar densities are reached on these small scales. In the surroundings of the protostar Cep A HW2 the results of Curriel et al. (2002) and Martín-Pintado et al. (2005) imply the presence of at least four embedded young stellar objects within a projected area of \( \sim 0.8'' \times 0.8'' \) (600 \( \times \) 600 AU\(^2\)). If we assume that the physical depth of the region equals its projected extent, we obtain a stellar density of \( 1.6 \times 10^8 \) stars pc\(^{-3}\). Thus, the initial conditions of our simulation, a small group of a few stars in a region with dimensions of a few hundred AU, are consistent with the observations of the Cep A HW2 region. An additional example of high stellar densities can be found in the \( \theta^1 \) Ori group. This more evolved system is composed of five stars within about 1'' of each other (Close et al. 2003), which, at the distance of Orion, corresponds to about 400 AU. The stellar density in this group is similar to that of the Cep A HW2 region.

Preliminary results of the first 100 five-body cases fully confirm our earlier findings. We find that a sizable fraction of such compact configurations produces one or more escapers with large velocities (greater than about 30 km s\(^{-1}\), i.e., runaway stars), after only about 2 crossing times. The positive energy carried away by the high-velocity escapers is compensated by the formation of a tight binary or multiple. In over 70% of the cases the binary was composed of the two most massive stars. To illustrate the dynamical evolution of such compact multiple systems we plot in Figures 3 and 4 final positions and velocities (after 2.2 crossing times, corresponding to about 650 yr) for two five-body examples. The similarity of these examples to the observed configuration of the BN system (Fig. 2; see also Fig. 3 in Gómez et al. 2005) is evident, if one takes into account the uncertainties in the estimated masses. Nevertheless, these simulations are just an illustration of the physical process, and explore a small range of the possible parameters. A forthcoming paper will present results of many more \( N\)-body realizations of several variants of the initial configurations (C. Allen & A. Poveda, in preparation). We emphasize that the initial conditions we chose were not the result of “integrating backward” the observed positions and velocities of BN, I, and \( n \), but were taken to simulate very dense stellar conditions such as those observed in some small scale (hundreds of AU) regions of massive star formation.

5. HOW CLOSE WERE BN AND SOURCE I IN THE PAST?

As we will see below, it is important to estimate how close BN and source I were in the past, during their minimum separation in the plane of the sky. Fortunately, this minimum separation can be estimated accurately using relative astrometry between BN and source I. We define \( x(t) \) and \( y(t) \) as the separations in right ascension and declination of BN with respect to source I as a function of epoch \( t \). If we assume that their proper motions are linear, the displacements will be given by

\[
x(t) = x(t=0) + \mu_x(t - 2000.0), \\
y(t) = y(t=0) + \mu_y(t - 2000.0),
\]
where \(x(2000.0)\) and \(y(2000.0)\) are the displacements in right ascension and declination for epoch 2000.0, and \(\mu_x\) and \(\mu_y\) are the proper motions in right ascension and declination. These constants and their errors can be determined very accurately from the relative astrometry.

The separation of the sources as a function of time, \(s(t)\), will then be given by

\[
s(t) = \left[ x^2(t) + y^2(t) \right]^{1/2}.
\]

Differentiating and equaling to 0, we find that this minimum separation takes place at an epoch \(t_{\text{min}}\) given by

\[
t_{\text{min}} = \frac{x(2000.0)\mu_y - y(2000.0)\mu_x}{\mu_x^2 + \mu_y^2},
\]

and that this minimum separation is

\[
s_{\text{min}} = \frac{|x(2000.0)\mu_y - y(2000.0)\mu_x|}{\left(\mu_x^2 + \mu_y^2\right)^{1/2}}.
\]

The least-squares fit to 14 data points from the VLA archive (shown in Table 3 and Fig. 5) gives \(x(2000.0) = -5.94'' \pm 0.21''\), \(\mu_x = -0.0125'' \pm 0.0004''\) yr\(^{-1}\), \(y(2000.0) = 7.73'' \pm 0.22''\), and \(\mu_y = 0.0144'' \pm 0.0004''\) yr\(^{-1}\). These values give a total proper motion of \(\mu_{\text{tot}} = 0.0191'' \pm 0.0004''\) yr\(^{-1}\) at a P.A. of \(-41.0^\circ \pm 2.0^\circ\). The proper motions are consistent within error, but more accurate, than those reported by Tan (2004) and Rodriguez et al. (2005). With these new values, we obtain

\[
t_{\text{min}} = 1490 \pm 11,
\]

\[
s_{\text{min}} = 0.55'' \pm 0.16'',
\]

where the errors were calculated using standard propagation error theory (Wall & Jenkins 2003). We conclude that, about 500 yr ago, BN and source I were within \(\sim 230 \pm 70\) AU from each other in the plane of the sky.

6. WAS BN EJECTED FROM \(\theta^1\) C Ori?

An alternative origin for the proper motions of BN has been proposed by Tan (2004). In his scenario, the ejection of BN took place from the \(\theta^1\) C Ori binary system. While this model is attractive because \(\theta^1\) C Ori is a massive, hard, and eccentric binary as required by such a dynamical event, our accurate relative
astrometry seems to rule out a close encounter between BN and $\theta^1$ C Ori in the past.

Tan (2004) made a comparison between the proper motions of BN (determined relatively to source I), $\mu_\alpha \cos \delta = -11.1 \pm 2.2$ mas yr$^{-1}$; $\mu_\delta = +14.3 \pm 2.2$ mas yr$^{-1}$, and the optical proper motions of $\theta^1$ C Ori determined by van Altena et al. (1988), $\mu_\alpha \cos \delta = +1.4 \pm 0.17$ mas yr$^{-1}$; $\mu_\delta = -1.8 \pm 0.16$ mas yr$^{-1}$. We note that the proper motions determined by van Altena et al. (1988) are not in an absolute reference frame (their system is defined by the average proper motions of their reference stars), and the reliability of the comparison is uncertain. Tian et al. (1996) have discussed the different reference frames for the proper motions of stars in Orion obtained by five different groups and find that they differ at the ~1 mas yr$^{-1}$ level. Furthermore, none of these reference frames is absolute in the sense of being referred to remote quasars. In any case, for the sake of discussion, we have followed the steps made by Tan (2004) to compare the proper motions of BN and of $\theta^1$ C Ori and used our relative astrometry for the proper motions of BN with respect to source I (consistent, but about 5 times more accurate than those of Tan), as well as the proper motions of van Altena et al. (1988) for $\theta^1$ C Ori. Making the same analysis as the one made in § 5 for the motions of BN with respect to source I, we obtain $x(2000.0) = -35.2'' \pm 0.2''$, $\mu_\alpha \cos \delta = -0.0139'' \pm 0.0004''$ yr$^{-1}$, $y(2000.0) = 60.2'' \pm 0.2''$, and $\mu_\delta = 0.0162'' \pm 0.0004''$ yr$^{-1}$ for the relative proper motions between BN and $\theta^1$ C Ori. With these values, we obtain

$$t_{\text{min}} = -1216 \pm 62,$$
$$s_{\text{min}} = 12.5'' \pm 1.0'',$$

that is, the minimum separation between BN and $\theta^1$ C Ori took place about 3200 yr ago, but this minimum separation was large, more than 10 $\sigma$ away from the close approach required in the model of Tan (2004). This may be more tolerable, but then the proper motion of $\theta^1$ C Ori has a position angle with a large error, P.A. = $142^\circ \pm 25^\circ$, and the argument of the antiparallel alignment between the proper motions of BN and $\theta^1$ C Ori is not compelling anymore.

One possible way to realign the proper motions of BN with respect to $\theta^1$ C Ori in this scenario is to take into account that during its close passage near source I, BN may have suffered a gravitational deflection of several degrees (Tan 2004). In any case, the possibility that a moving massive star passes close to another massive star is very low. BN appears projected at about $70''$ from $\theta^1$ C Ori in the plane of the sky. This corresponds to a physical separation of $l \sim 4.3 \times 10^{17}$ cm. Within a sphere with this radius centered on $\theta^1$ C Ori there are of the order of 10 massive stars. This gives a local density of massive stars of $N_c \sim 8.9 \times 10^2$ pc$^{-3}$. The probability of an encounter between two stars at a minimum separation of $R = 200$ AU (as derived from the relative astrometry between BN and source I) is

$$p \approx N_c \pi R^2 l \approx 3.7 \times 10^{-4}.$$  

7. POSSIBLE DIFFICULTIES WITH THE CLUSTER DISINTEGRATION MODEL

Tan (2008) has pointed two possible difficulties with the model of the disintegrating cluster originally located between BN and source I proposed by Rodríguez et al. (2005) and Gómez et al. (2005). The first difficulty is related with the fact that in some molecular tracers (for example, the silicate line-of-sight extinction image of Gezari et al. 1998), source I appears located close to the peak, suggesting it is stationary with respect to the dense gas in the region.

However, other tracers show a different picture. The OH masers observed by Cohen et al. (2006; see their Figs. 1 and 8) clearly are distributed between source I and BN. These authors suggest that these masers trace shock fronts in a trail produced by the passage of the moving sources. Part of the OH masers show a torus morphology approximately centered at the position proposed by us to be the center of the BN, I, and $\eta$ ejection.

It is also relevant that in many tracers source I is not engulfed (this is, surrounded in all directions) in dust and molecular gas (Beuther et al. 2004; Wilson et al. 2000), but that these emissions
peak mostly to the southeast of I. This may be consistent with the 

motion of source I, ‘‘clearing’’ molecular gas in its path to the 
southeast.

The second possible difficulty pointed by Tan (2008) is related 
with the fact that if source I and source n are moving at velocities 
of 15–26 km s \(^{-1}\), why are then they able to retain the gas as-
sociated with them at the 100 AU scale? In our interpretation, 
this gas is the result of supersonic (hundreds of km s \(^{-1}\)) ejections 
from the associated stars, and we do not expect it to be affected 
by their motion at velocities an order of magnitude smaller with 
respect to the surrounding medium. However, if the new inter-
pretation of Reid et al. (2007) of source I as an ionized disk is 
correct, there is a problem in that it will be hard to understand 
how a source that had a close encounter in the recent past (500 yr 
ago with source I) has managed to rebuild and retain its cir-
sumstellar disk.

Finally, we note that also BN has associated ionized gas at the 
100 AU scale. The observed deconvolved size of BN at 3.6 cm is 
\(~0.17'' \times 0.08''\) (see Table 1) or \(~70 \text{ AU} \times 30 \text{ AU}\) at a distance 
of 414 pc. The explanation for this gas is usually in terms of a 
hypercompact H \(\Pi\) region, although other possible explanations 
have been discussed by Scoville et al. (1983). In Figure 7 we show 
a high angular resolution, high-sensitivity 7 mm image of BN, 
produced from the same data set that Reid et al. (2007) used 
to study the radio source I. The total flux density of the source 
at this wavelength is 26.4 \(\pm\) 0.7 mJy, and its deconvolved 
dimensions are 0.075'' \(\pm\) 0.003'' \(\times\) 0.042'' \(\pm\) 0.002''; P.A. = 
56° \(\pm\) 2°. The larger flux density and smaller angular dimensions 
observed at 7 mm with respect to 3.6 cm (see Table 1) are consist-
tent with those expected for a region of ionized gas in which the 
electron density decreases as a function of radius (Reynolds 1986).

But, if BN is moving, why do we not see a clear ‘‘tail’’ of 
recombining gas as expected for a star that moves in a stationary 
medium (Raga et al. 1997)? The solution is probably in the very 
fast recombination time of BN as compared with the time it takes 
BN to displace by a distance equal to its own diameter. Along the 
axis of motion, BN has an angular size of about 80 mas (30 AU 
at a distance of 414 pc). Moving at 10.8 mas yr \(^{-1}\), we expect that 
the source will displace a distance comparable with its size in a 
time of order 7 yr. For the recombining ‘‘tail’’ not to be detect-
able we need for the ionized gas in BN to have a recombination 
time much shorter than 7 yr. From the 7 mm observations of L. F. 
Rodrı´guez et al. (2008, in preparation) and from Moran et al. 
(1983) and Scoville et al. (1983), we estimate an electron density 

fig. 5.— Relative proper motions of BN with respect to source I. The data used 
for this graph are listed in Table 3. The dashed line is the weighted least-squares fit 
to the data points. The relative proper motions in right ascension and declination are 
\(\mu_x = -0.0125'' \pm 0.0004'' \text{ yr}^{-1}\) and \(\mu_y = 0.0144'' \pm 0.0004'' \text{ yr}^{-1}\), respectively.

fig. 6.— Orion BN/ KL and Trapezium region is shown in this figure. The sources 
BN and I are indicated (empty squares), as well as the components A, B, C, and 
D of the Trapezium (filled squares). The proper motion of BN with respect to 
source I is shown with an arrow that starts in BN and points to the northeast. The 
dashed lines that start in BN and point to the southeast indicate the past cone of 
uncertainty of the motions of BN. The arrow and dashed lines that start in \(\theta\) C Ori 
mark the proper motion and past cone of uncertainty of the motions of this source, 
respectively, taken from van Altena et al. (1988). In the arrows, 1'' represents 
0.5 mas yr \(^{-1}\).
of $2 \times 10^7$ cm$^{-3}$, that implies a very fast recombination time of only a few days. Then, we do not expect to see much of a recombining tail as BN moves in the surrounding medium.

### 8. COMMENTS ON INDIVIDUAL SOURCES IN THE BN/KL REGION

#### 8.1. Orion-n

This infrared source, detected by Lonsdale et al. (1982), has recently been studied at mid-IR wavelengths by Greenhill et al. (2004a), who infer a luminosity of order 2000 $L_\odot$ for it. The associated radio source was first reported by Menten & Reid (1995), who found it to be double in their VLA 3.6 cm image taken in 1994. Our data (see Fig. 8) show that in the 1991, 1995, and 2000 images the source has remained double, with a north-south separation of about 0.35$''$. Remarkably, in the 2006 image Orion-n appears as a single radio source. We believe that this morphological change is real and not a consequence of different angular resolutions since all the data analyzed have very similar angular resolution. This result suggests that an alternative explanation could be that the source has no real proper motions and that the apparent motion is a result of the southern component becoming much brighter than the northern one over the time baseline of the observations. However, the positions fitted (using the AIPS task JMFIT) to the 1991, 1995, and 2000 images assuming that two Gaussians are present (see Fig. 1) show a progressive shift in the position of the two components whose average extrapolates well to the position of the single component used to fit the 2006 image.

The positions of the individual components of the double radio source for 1991, 1995, and 2000 as well as that of the single source in 2006 are shown in Figure 1. The northern and southern components of the double source for the first three epochs have been fitted with dashed lines, while all components have been fitted to a solid line. This figure shows that the single source observed in 2006 is the centroid of the double source seen in the other epochs and not one of the components that became dominant.

Greenhill et al. (2004a) and Shuping et al. (2004) have analyzed their mid-infrared images of Orion-n and conclude that it is slightly elongated (at the arcsecond scale) in the east-west direction, suggesting that it may trace a disklike structure approximately perpendicular to the axis joining the double radio source. From submillimeter observations of the dust emission from this source, Beuther et al. (2004) estimate a mass of about 0.27 $M_\odot$ for the associated gaseous structure, a value consistent with that expected for the disk of a massive young star. Under this interpretation, the radio emission from source n would be tracing an ionized outflow, or thermal jet. Although not frequent in bipolar ionized outflows, the change from double-peaked to single-peaked source, and vice versa, has been observed in a handful of sources (Cohen et al. 1982; Bieging et al. 1984; Rodríguez et al. 2007; Loinard et al. 2007) and is possibly caused by the ejection of clumps of ionized gas. However, the reason for the morphological change observed in the radio counterpart to Orion-n is unclear, and additional observations are required to understand it.

Despite the dramatic changes in its morphology, the total 3.6 cm flux density of source n does not appear to have undergone...
very large changes over the four epochs of the observations, ranging from 1.5 to 2.2 mJy. The total 3.6 cm flux density measured in 1994 by Menten & Reid (1995), 2.0 mJy, also falls in this range. The position shifts observed in this source could potentially be due to morphological changes. Nevertheless, the systematic displacement of the positions over four epochs favors the more straightforward interpretation of true proper motions.

8.2. GMR I

Greenhill et al. (2004b) and Reid et al. (2007), based on the interpretation of the SiO and H$_2$O emission observed around source I, proposed a model with a rotating disk and a wide angle outflow pointing in the northeast-southwest direction. This model is proposed to replace that of Greenhill et al. (1998) in which the SiO masers were proposed to form in the limbs of a high-velocity biconical outflow projected along a northwest-southeast axis. Clearly, this source needs to be observed in even greater detail to elucidate its nature and to determine its mass.

8.3. BN

Grosso et al. (2005) have discussed the presence of two X-ray sources near BN: COUP 599a and COUP 599b. They conclude that neither source is BN itself, but most probably deeply embedded lower mass stars, either unrelated or companions to BN.

8.4. GMR D

This radio source is associated with an X-ray source from the Chandra Orion Ultradeep Project Census (Source COUP 662; Grosso et al. 2005), but it has no optical or near-infrared counterpart. The association with X-ray emission suggests it could be a T Tau star. It shows no statistically significant proper motions. We confirm its known variability at radio wavelengths (e.g., Zapata et al. 2004), since we observe its flux density to vary between 0.7 and 4.2 mJy over the four epochs.

8.5. The Transient Radio Source

During the 2006 observations we detected an unresolved radio source at position $\alpha$(J2000.0) = 05$^h$35$^m$14.6565$^s$; $\delta$(J2000.0) = $-$05$^\circ$22$'$33.731$''$, with total flux density of 1.3 ± 0.1 mJy. The radio source is located within 0.1” of the K7 star Parenago 1839, and we propose they are the same object. The source is also associated within 1” with the X-ray source COUP J053514.6-052233. Unfortunately, the radio emission was not detected in the previous three epochs and we do not have a proper motion for this source. To our knowledge, this is the first radio detection of this source, marked in Figure 2 as Parenago 1839.

9. CONCLUSIONS

We have confirmed the large proper motions, with values from 15 to 26 km s$^{-1}$, found for the radio sources associated with the BN object, the radio source I, and the infrared source Orion-n. All three sources appear to be diverging from a point in between them, from where they were apparently ejected about 500 yr ago, probably via the disintegration of a compact multiple stellar system. We present simulations of the dynamical evolution of very compact groups of stars that illustrate the physical process. These theoretical results imply that these stars were part of a very dense young compact group (<10$^5$ stars pc$^{-3}$), like those observed today in small regions associated with Cep A HW2 and $\theta$ B Ori.

The radio source associated with the infrared source shows a large morphological change in the 2006 image, where after being observed as double for many years, it appears as a single source. We believe that this behavior is consistent with an interpretation in terms of a thermal jet.

Finally, in the Appendix we report a rapid centimeter flare during the 2006 observations in the source GMR A, of similar characteristics to that observed at millimeter wavelengths in 2003.

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APPENDIX

RAPID VARIABILITY IN GMR A

The GMR A source is a strongly variable radio source (Garay et al. 1987; Felli 1993a, 1993b), a bright near-infrared point source (No. 573; Hillenbrand & Carpenter 2000), and a variable X-ray source (No. 297; Feigelson et al. 2002). Bower et al. (2003a) reported the serendipitous discovery of a giant flare at 86 GHz from this radio source with the Berkeley-Illinois-Maryland Array (BIMA) on 2003 January 20, with a flux density that increased by a factor of more than 5 on a timescale of hours. The follow-up observations of Bower et al. (2003b) with BIMA and the VLA and of Furuya et al. (2003) with the Nobeyama Millimeter Array showed that the source decayed within days of the outburst. These authors found GMR A to be highly variable at 15 and 22 GHz on a timescale of hours to days during the period of the millimeter flare, and the source is well known to be variable at centimeter wavelengths, at least in the timescale of weeks to years (Felli et al. 1993b; Zapata et al. 2004).

During the 2006 run, we found a rapid flux density increase by a factor of ~3.5 over a timescale of about 1 hr (see Fig. 9). The flare observed at centimeter wavelengths is remarkably similar to that observed previously in the millimeter. The increase is in both cases on the order of a few and the rise timescale is of order 1 hr. Furthermore, the circular polarization (see Fig. 9) was in both cases of order (V/I) ~ 5% to ~10% before the flare and, as emphasized by Bower et al. (2003b) in the case of the millimeter flare, no circular polarization is detected near the peak of the flare. We also note that the variations in the flux density of the source are larger before than during the flare (see Fig. 8).

This source is ~1' to the northwest of the phase center of the observations, and its astrometry is not as reliable as that of the four sources previously discussed. We have assumed that the real error associated with its positions is twice that given by the formal fit. From our data, we derive proper motions of $\mu_\alpha \cos \delta = +4.8 \pm 1.8$ mas yr$^{-1}$; $\mu_\delta = -1.6 \pm 2.1$ mas yr$^{-1}$, that are consistent at the 2 $\sigma$ level with the values reported by Gómez et al. (2005), Sandstrom et al. (2007), and Menten et al. (2007). The values of Sandstrom et al. (2007) and Menten et al. (2007) were obtained from VLBI observations and should be very accurate.

A similar flare was reported recently by Forbrich et al. (2008) at 1.3 cm toward the Orion radio source ORBS J053514.67-052211.2.
Fig. 9.—Stokes I (top) and percentage of circular polarization (bottom) for the source GMR A during the 2006 May 12 flare.

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