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

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RESUMEN

Presentamos astrometría absoluta de cuatro fuentes de radio en la región de Becklin-Neugebauer/Kleinman-Low (BN/KL), derivados de datos de archivo (tomados en 1991, 1995, y 2000) así como de nuevas observaciones (tomadas en 2006). Todos los datos consisten de emisión de continuo a 3.6 cm tomados con el Very Large Array en su configuración A, la de más alta resolución angular. Confirmamos las grandes velocidades transversales del objeto BN, la fuente de radio I (GMR I) y la contraparte de radio de la fuente infrarroja n (Orion-n), con valores de 15 a 26 km s^{-1}. Las tres fuentes se alejan de un punto entre ellas de donde parecen haber sido eyectadas hace alrededor de 500 años, probablemente como resultado de la desintegración de un sistema estelar múltiple. La fuente de radio Orion-n aparecía como doble en las tres primeras épocas, pero como sencilla en 2006. La cuarta fuente de la región, GMR D, no muestra movimientos propios estadísticamente significativos. También discutimos brevemente un escenario dinámico para la región.

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 transverse velocities 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. The radio source Orion-n appeared as a double in the first three epochs, but as single in 2006. The fourth source in the region, GMR D, shows no statistically significant motions. We also discuss briefly a dynamical scenario for the region.

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

1. INTRODUCTION

For more than three decades, the Orion BN/KL region has been known to be at the center of a remarkable, fast (30–100 km s^{-1}), and massive ($\sim$ 10 $M_\odot$) outflow, with a kinetic energy of order 4×10^{47} ergs, which Kwan & Scoville (1976) ascribe to an explosive event and which also manifests itself as shock excited molecular hydrogen (H_2) emission at near infrared wavelengths (Beckwith et al. 1978). This outflow was later resolved into "fingers" of H_2 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).

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 Orion-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 point where they must all have been located about 500 years 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 simul-

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taneously 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 source BN, I, and n. Finally, we discuss a dynamical scenario that accounts for the observed high velocity of the stellar objects.

2. OBSERVATIONS

We have used 3.6 cm data from the Very Large Array of NRAO[4] 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 06, 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 (Bridle & Greisen 1994) 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 longer than 100 kλ, suppressing the emission from structures larger than $2''$.

3. RESULTS

We have used these multiepoch VLA observations taken over 15 years (1991–2006) to study the proper motions of the four persistent and compact radio sources clearly detectable in the BN/KL region (Figures 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 1). The proper motions of all four sources are consistent within 1-σ 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 transverse velocities of BN, I, and n are in the range of 15 to 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, Moran, & Reid 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 Figure 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 been 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}.

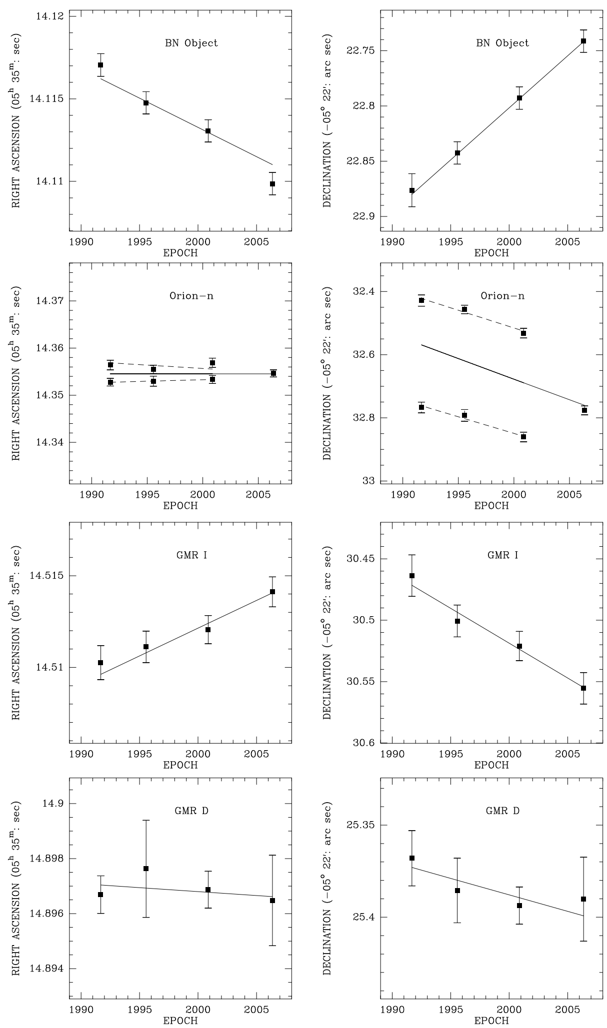

Fig. 1. Proper motions for the four persistent radio sources in the Orion BN/KL region. The solid lines are the least-squares fits to the data. The proper motions of source Orion-n are described in the text.

[4]The National Radio Astronomy Observatory (NRAO) is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.

TABLE 1

ABSOLUTE PROPER MOTIONS OF THE RADIO SOURCES[a]

Source	$\mu_\alpha \cos\delta$ (mas yr^{-1})	μ_δ (mas yr^{-1})	μ_{total} (mas yr^{-1})	P.A. (°)
BN object	-5.3 ± 0.9	9.4 ± 1.1	10.8 ± 1.0	$-29{\pm}5$
Orion−n[b]	0.0 ± 0.9	-13.0 ± 1.2	13.0 ± 1.2	$180{\pm}4$
GMR I	4.5 ± 1.2	-5.7 ± 1.3	7.3 ± 1.2	$142{\pm}10$
GMR D	-0.4 ± 1.3	-1.8 ± 1.6	1.8 ± 1.6	$-166{\pm}42$

[a]The errors quoted in this table are 1–σ.

[b]See text for the proper motions reported here.

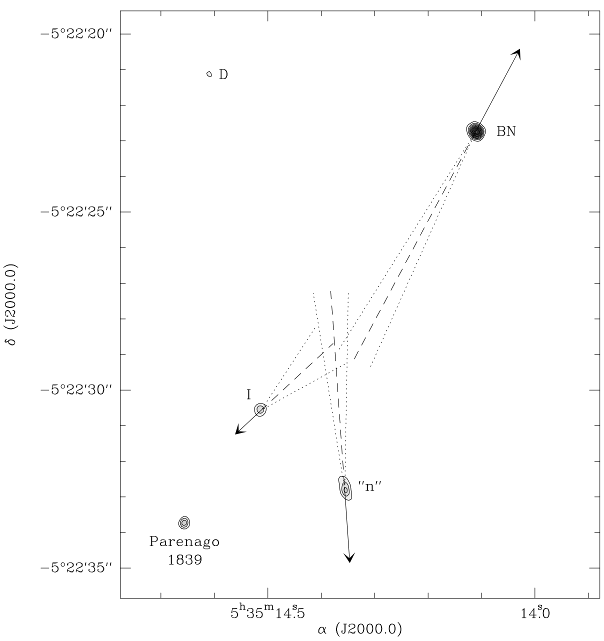

Fig. 2. VLA contour image at 8.46 GHz toward the Orion BN/KL region for epoch 2006.36. The first contour is 300 μJy beam^{-1} and increments are in units of 150 μJy beam^{-1}. The angular resolution of the image is $0.''26 \times 0.''22$; PA $= -2°$. The individual radio sources are identified. The arrows indicate the direction and proper motion displacement for 200 years, 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.

3.1. *Orion-n*

This infrared source, detected by Lonsdale et al. (1982), has recently been studied at mid-IR wavelengths by Greenhill et al. (2004) who infer a luminosity of order 2,000 $L_\odot$ for it. The associated radio source was first reported by Menten & Reid (1995; their source "L"), who found it to be double in their VLA 3.6 cm image taken in 1994. Our data (Gómez et al., in prep.) shows 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.

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. 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.

Greenhill et al. (2004) and Shuping, Morris, & Bally (2004) have analyzed their mid-infrared images of Orion-n and conclude that it is slightly elongated (at the arc sec scale) in the east-west direction, suggesting that it may trace a disk-like structure approximately perpendicular to the axis joining the double radio source. 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 viceversa, has been observed in a handful of sources (e. g. Loinard et al. 2007), and is possibly caused by the ejection of clumps of ionized gas.

4. A DYNAMICAL SCENARIO FOR THE REGION

The mass of BN is estimated to be 8 $M_\odot$ < M_{BN} < 18 $M_\odot$ (Scoville et al. 1983; Rodríguez et al. 2005). Since source n is moving with the largest proper motion, for simplicity we assume 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 1, conservation of linear momentum along the direction of motion of BN implies that the mass of source I is $M_I < 1.5\ M_{BN}$, i.e., 12 $M_\odot < M_I <$ 27 $M_\odot$. We identify source I with a close binary formed by dynamical interactions that has the negative binding energy of the system. Energy conservation implies that the semimajor axis of the binary is given by $a/\mathrm{AU} = 35.4\, f\,(1-f)(M_{BN}/18\ M_\odot)$, where f is the mass fraction of the primary. Thus, the maximum possible binary separation, for $f = 1/2$ (equal masses), is $a = 8.9(M_{BN}/18\ M_\odot)$ AU. These estimates have taken into account a small correction due to the expected radial velocities of these sources (Rodríguez et al. 2005). Finally, conservation of linear momentum in the direction perpendicular to the motion of BN implies that the mass of source n is $M_n = 0.16\ M_I$, i.e., 1.9 $M_\odot < M_n <$ 4.3 $M_\odot$.

Using the masses estimated above, the kinetic energy involved in the three kinematically peculiar objects, BN, I and n, is of order $\sim 2 \times 10^{47}$ergs. To accelerate these objects to their observed velocities from the typical small random motions of recently formed stars (1–2 km s^{-1}), one can invoke very close encounters in a multiple star system, as first proposed by Poveda, Ruiz, & Allen (1967). We have recently updated these computations, using the chain-regularization N-body code of Mikkola & Aarseth (1993). The results illustrated in Poveda et al. (1967) were exactly reproduced by the new computations.

For the new examples, we simulated compact multiples composed of 5 stars of different masses (ranging from 8 to 20 $M_\odot$), densely packed within radii of 400 AU ($\sim$0.0019 pc) and with a velocity dispersion corresponding to the thermal velocity at a temperature of 10 K. The stellar density required is thus 1.6×10^8 stars pc^{-3}. 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. A forthcoming paper will present results of many more N-body realizations of several variants of the initial configurations (Allen & Poveda, in prep.).

5. CONCLUSIONS

We have confirmed the large transverse velocities, 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 years ago, probably via the disintegration of a compact multiple stellar system. We discuss 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.

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