The Astrophysical Journal, 834:140 (8pp), 2017 January 10 doi:10.3847/1538-4357/834/2/140

THE PROPER MOTIONS OF THE DOUBLE RADIO SOURCE n IN THE ORION BN/KL REGION

Luis F. Rodríguez[1], Sergio A. Dzib[2], Laurent Loinard[1,2], Luis Zapata[1], Laura Gómez[3,4,5], Karl M. Menten[2], and Susana Lizano[1]

[1] Instituto de Radioastronomía y Astrofísica, UNAM, Apdo. Postal 3-72 (Xangari), 58089 Morelia, Michoacán, México; l.rodriguez@crya.unam.mx
[2] Max Planck Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[3] Joint ALMA Observatory, Alonso de Córdoba 3107, Vitacura, Santiago, Chile
[4] CSIRO Astronomy and Space Science, P.O. Box 76, NSW 1710 Epping, Australia
[5] Departamento de Astronomía, Universidad de Chile, Camino El Observatorio 1515, Las Condes, Santiago, Chile
Received 2016 September 3; revised 2016 October 28; accepted 2016 November 18; published 2017 January 11

ABSTRACT

We have extended the time baseline for observations of the proper motions of radio sources in the Orion BN/KL region from 14.7 to 22.5 years. We present improved determinations for the sources BN and I. In addition, we address the proper motions of the double radio source n, that have been questioned in the literature. We confirm that all three sources are moving away at transverse velocities of tens of kilometers per second from a region in-between them, where they were located about 500 years ago. Source n exhibits a new component that we interpret as due to a one-sided ejection of free–free emitting plasma that took place after 2006.36. We used the highly accurate relative proper motions between sources BN and I to determine that their closest separation took place in the year 1475 ± 6, when they were within ∼100 au or less from each other in the plane of the sky.

Key words: astrometry – stars: formation – stars: individual (BN, I, n) – radio continuum: stars

1. INTRODUCTION

The Orion BN/KL region has long been known to exhibit evidence of a violent explosive phenomenon that took place some 500 years ago (e.g., Bally & Zinnecker 2005; Gómez et al. 2008). Filaments of molecular gas (the so-called Orion H_2 fingers; e.g., Bally et al. 2015; Youngblood et al. 2016) are moving away from a common origin at velocities in the range of tens to hundreds of kilometers per second. The inner parts of this outflowing molecular gas have been imaged in CO by Zapata et al. (2009) and exhibit the same behavior. Three compact radio sources, believed to trace stellar objects, are also known to recede from the same location at transverse velocities in the range of 15–26 km s^{-1} (Gómez et al. 2008). The proper motions of these compact objects, known as sources BN, I, and n, have also been studied by Goddi et al. (2011), who confirmed the proper motions for sources BN and I previously determined by Gómez et al. (2008) but noted that their measurements were consistent with a null proper motion for source n. In this paper we reanalyze the proper motions of these compact radio sources taking advantage of the existence of new observations of high quality. The data discussed here cover the period from 1991.67 to 2014.17, about 50% larger than that used by Gómez et al. (2008). Since the accuracy of the proper motion determinations improves with time as $t^{3/2}$ (Dzib et al. 2017) our results are about a factor of 2 more accurate than those reported in Gómez et al. (2008).

2. OBSERVATIONS

To improve the determination of the proper motions of sources BN, I, and n, we analyzed Very Large Array (VLA) and Jansky VLA archive observations made at seven epochs between 1991.67 and 2014.17. In the case of the bright radio source BN we were able to add a previous observation of lower sensitivity made in 1985.05. These epochs were selected on the basis of a combination of the best angular angular resolution and sensitivity. In particular, all are made in the highest angular resolution A configuration possible. On the other hand, in the case of source n we did not take into account the observations of 2011.56 when the emission was seriously affected by free–free emission from a cloud of ionized gas (see below for a detailed discussion). The data were analyzed in the standard manner using the AIPS (Astronomical Imaging Processing System) and the CASA (Common Astronomy Software Applications) packages of NRAO, the former one for the VLA observations and the latter one for the Jansky VLA observations. In the calibration stage we used the pipeline provided for Jansky VLA observations by NRAO. The final analysis and production of contour images were all made within the older but more mature AIPS software. A detailed analysis of a subset of the data is presented in Gómez et al. (2008).

In Table 1 we show the proper motions determined for sources BN, I, and n. The proper motions were calculated adding in quadrature systematic errors of order $\sim 0.''01$ to the formal position uncertainties to obtain a reduced $\chi^2 = 1$. The proper motions for source BN and I coincide within about ± 1–σ to ± 2–σ with those of Gómez et al. (2008). This result supports a ballistic (i.e., unaccelerated) motion for these two sources. The interpretation of the proper motions of source n will be discussed below.

3. INDIVIDUAL PROPER MOTIONS

3.1. Sources BN and I

In the bottom panels of Figures 1 and 2 we show contour images of these two sources for epochs 1991.67 and 2012.76, where the displacement is evident. In the top panels of these figures we also show the positions of sources BN and I as a function of time. Clearly, the motions follow a straight line within the noise.

3.2. The Double Source n and Associated Ejecta

We now discuss the proper motions of the double source n. Source n appeared as double in the north–south direction for

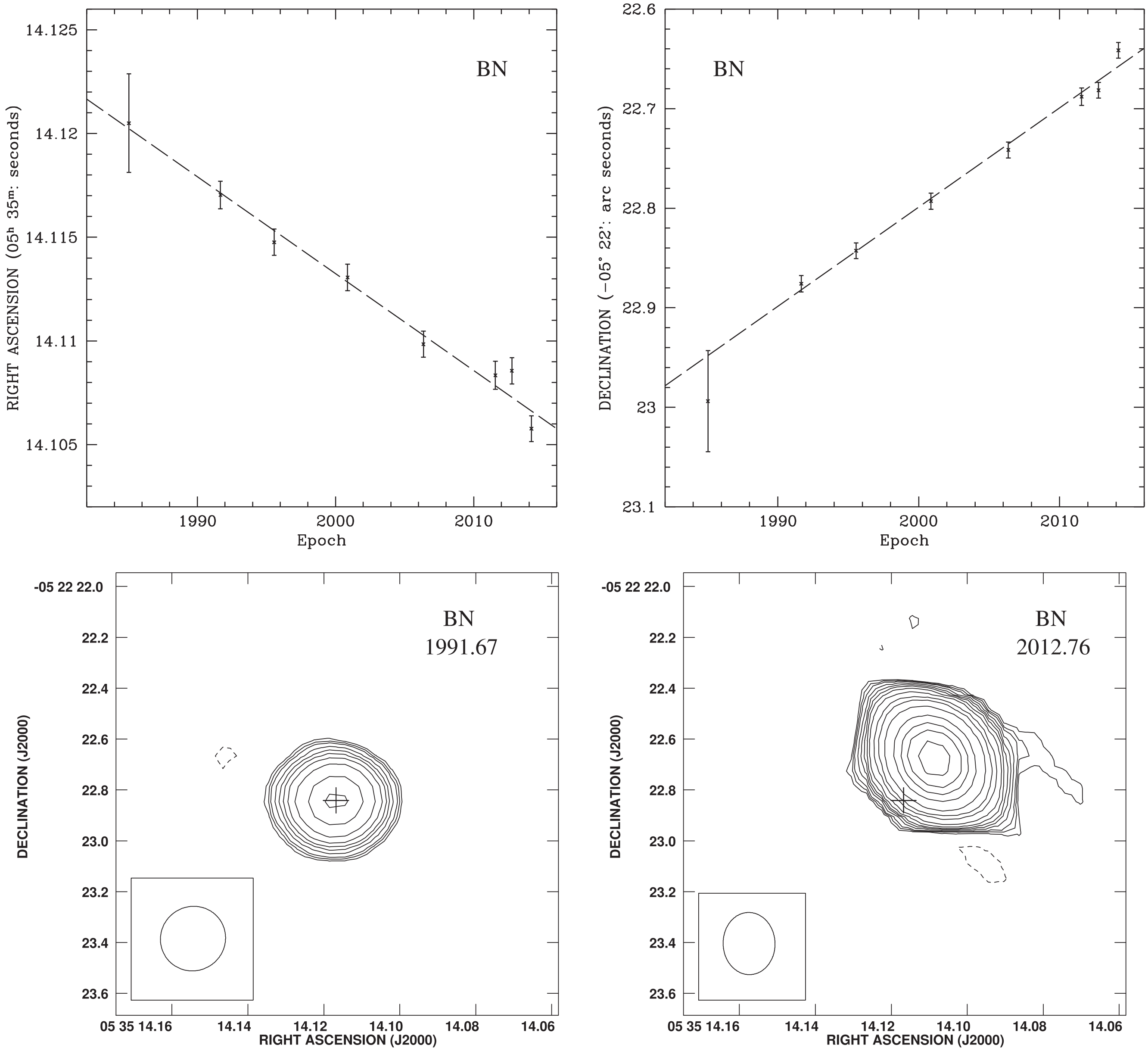

Figure 1. Top left: proper motions in right ascension for source BN. Top right: proper motions in declination for source BN. The dotted line is a least-squares linear fit to the data. The resulting proper motions are given in Table 1. Bottom left: VLA 8.4 GHz continuum contour image of the source BN for epoch 1991.67. The contours are −4, 4, 5, 6, 8, 10, 12, 15, 20, 30 and 40 times 88 μJy beam^{-1}, the rms noise of the image. The half-power contour of the synthesized beam is shown in the bottom left corner ($0\overset{''}{.}26 \times 0\overset{''}{.}25$; PA = −55°). The cross marks the peak position of the emission for epoch 1991.67. Bottom right: JVLA 7.3 GHz continuum contour image of the source BN for epoch 2012.76. The contours are −4, 4, 5, 6, 8, 10, 12, 15, 20, 30, 40, 60, 100, 200, and 250 times 10 μJy beam^{-1}, the rms noise of the image. The half-power contour of the synthesized beam is shown in the bottom left corner ($0\overset{''}{.}24 \times 0\overset{''}{.}20$; PA = 2°). The cross marks the peak position of the emission for epoch 1991.67. The parameters of the fits to the proper motions are given in Table 1.

Table 1
Parameters of Radio Sources in the Orion BN/KL Region

Name	Position[a]		Flux Density[b]	Proper Motions[c]		Total Proper Motion[d]
	α(J2000)	δ(J2000)	(mJy)	$\mu_{\alpha} cos\delta$	μ_{δ}	Magnitude; PA
BN	$05^h35^m14\overset{s}{.}110$	$-05°22'22\overset{''}{.}67$	4.06 ± 0.20	−7.0 ± 0.4	+10.0 ± 0.4	12.2 ± 0.4; −35 ± 2
n	$05^h35^m14\overset{s}{.}357$	$-05°22'32\overset{''}{.}78$	1.45 ± 0.03	+1.1 ± 0.9	−8.6 ± 0.6	8.7 ± 0.6; +173 ± 4
I	$05^h35^m14\overset{s}{.}516$	$-05°22'30\overset{''}{.}59$	0.98 ± 0.05	+2.9 ± 0.4	−5.4 ± 0.4	6.1 ± 0.4; +152 ± 4

Notes.
[a] Equinox J2000.0 and epoch 2012.76.
[b] At the frequency of 7.3 GHz.
[c] In mas yr^{-1}.
[d] Magnitude in mas yr^{-1}, PA in degrees.

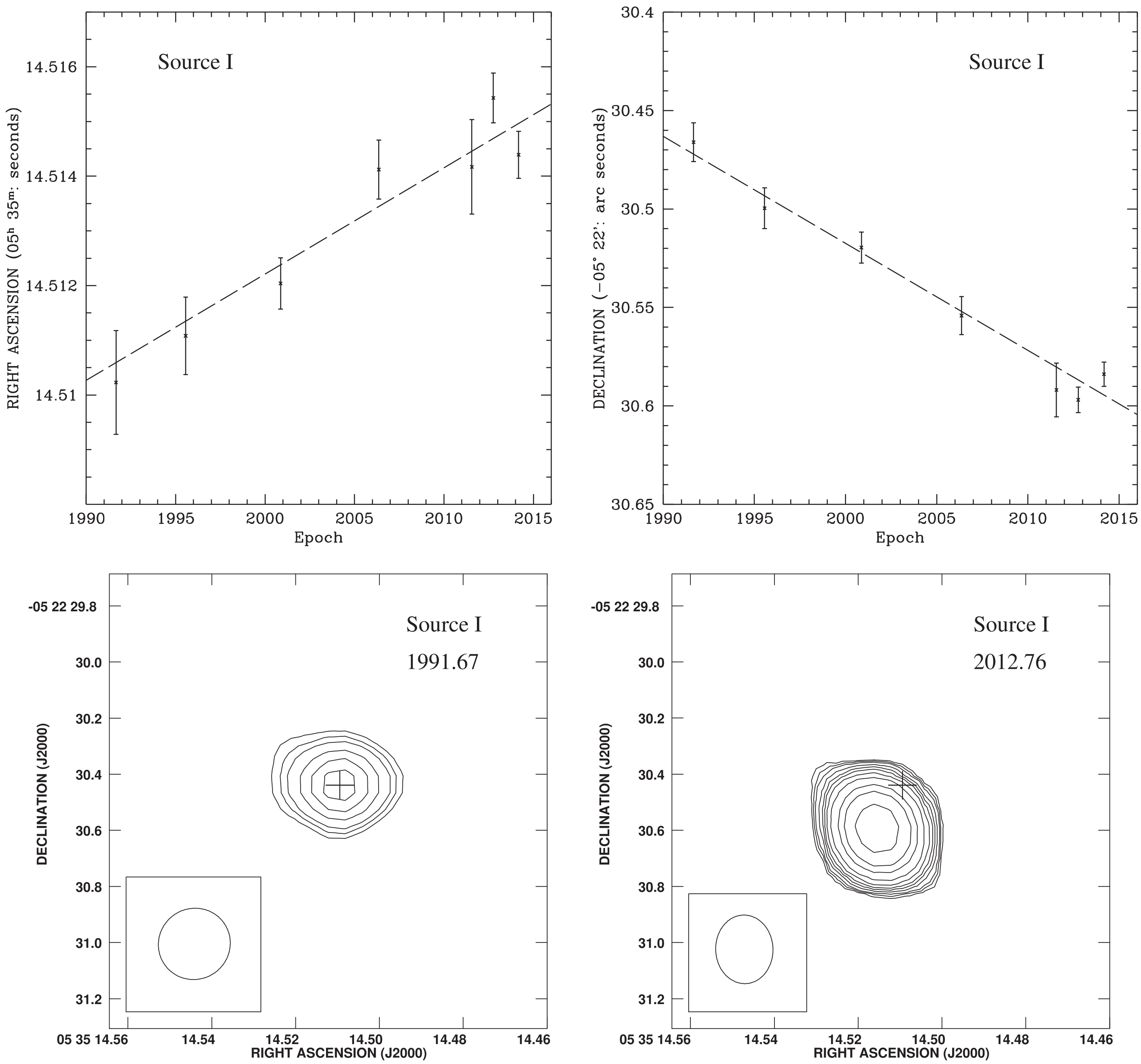

Figure 2. Same as in Figure 1 but for source I.

the three observations made in the period from 1991.67 to 2000.87 (see Figure 8 of Gómez et al. 2008). We will refer to these components as nN and nS. However, by 2006.36 the double source appeared unresolved, as a single elongated object (see Figure 8 of Gómez et al. 2008). In Figure 3 we show contour images for epochs 1991.67 and 2012.76. The image for 1991.67 clearly shows the double morphology. The image for 2012.67 is complex and can be described as constituted of two components, but much more separated and of different morphology than those components seen in 1991.67. We interpret this image as follows. The northern component is taken to be the double source that remains spatially unresolved, as first observed in 2006.36. The southern component is interpreted as a cloud of ionized plasma that was ejected from one of the stars in the double system sometime after 2006.36.

The proper motions reported in Table 1 and shown in Figure 3 are obtained from fitting the double stellar component, with the position being the average of the double source, or the centroid of a single elongated source when the double source was not resolved (which is the case for all images taken after 2006.36). This set of data contains two new observations with respect to the data used by Gómez et al. (2008). New observations over the following years are needed to test if the proper motions reported here predict the future position of the centroid of the double stellar source.

If we assume that the ejection took place after 2006.36, we can estimate lower limits to the proper motion of the ejecta from the position shown in Figure 3. If we assume that it was ejected from the northern stellar component, we obtain a lower limit for the proper motion of $\geqslant 110$ mas yr^{-1}, while if it was ejected from the southern stellar component we obtain a lower

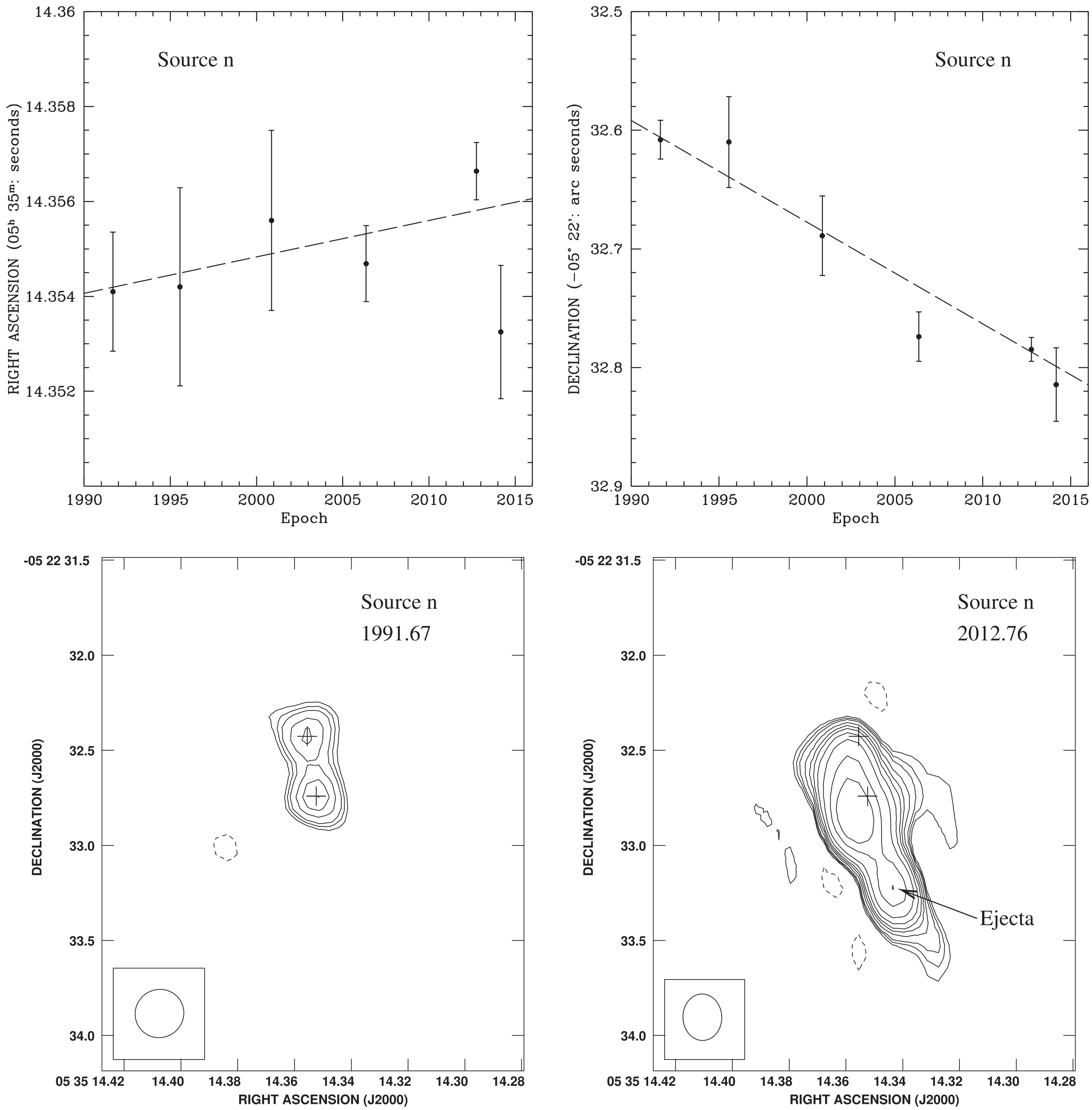

Figure 3. Same as in Figure 1 but for source n. In the image of 2012.76 the arrow indicates the component that is interpreted as recent ionized ejecta.

limit for the proper motion of ⩾60 mas yr^{-1}. At a distance of 414 pc (Menten et al. 2007, see however a new estimate of 388 pc by Kounkel et al. 2016), these proper motions are equivalent to velocities in the plane of the sky of 220 km s^{-1} and 120 km s^{-1}, respectively. These velocities are comparable to those observed in the proper motions of ejecta from young, intermediate-mass stars (e.g., Rodríguez-Kamenetzky et al. 2016).

The ejecta has to be dominantly one-sided (approximately to the south), because we do not see a major distortion in the northern component. One-sided ejecta (sometimes called monopolar or asymmetric jets) from young stars are not uncommon and have been observed in sources such as OMC 1 South (Zapata et al. 2006), DG Tau (Rodríguez et al. 2012b), DG TauB (Rodríguez et al. 2012a), HH 111 (Gómez et al. 2013), NGC 1333-IRAS2A (Codella et al. 2014), and Serpens SMM1 (Hull et al. 2016).

3.3. Testing the Plasma Ejection Scenario

There are two ways to test this scenario. First, if the emission observed recently to the south of the double source is produced by ejected plasma, we expect the ejecta to become fainter on a recombination timescale. From the 2012.76 observations (see

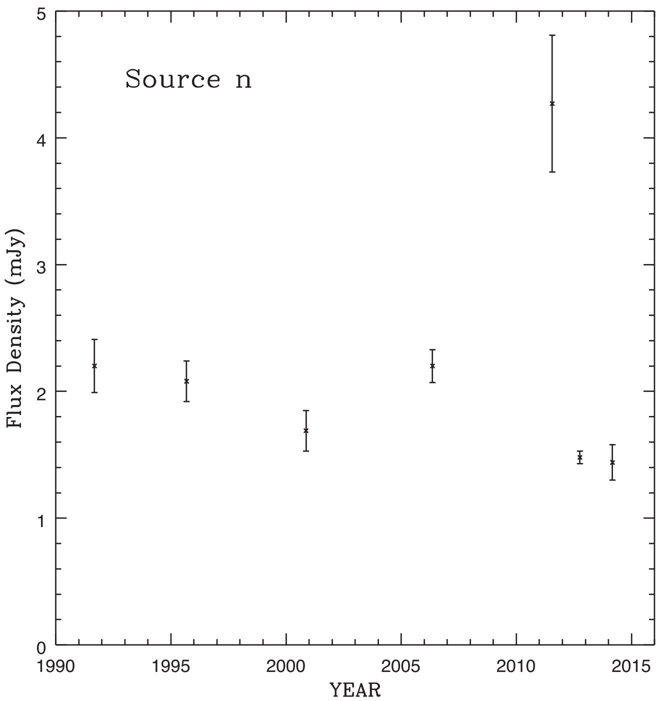

Figure 4. 8.4 GHz flux density for source n as a function of time. The increase for epoch 2011.56 is proposed to be associated with the ejection. These flux densities have been obtained at somewhat different frequencies and have all been normalized to a frequency of 8.4 GHz following the results of Forbrich et al. (2016) that imply that the frequency dependence of the centimeter flux density of source n is given by $S_\nu \propto \nu^{-0.3}$.

Figure 3), we measure a flux density for the southern condensation of $S_{7.3\,\mathrm{GHz}} = 0.45$ mJy, and an angular size $\theta_s^2 < (0\rlap{.}''2)^2$. Assuming optically thin free–free emission, an electron temperature $T_e = 10^4$ K, the emission measure is $\mathrm{EM} = n_e^2 l \gtrsim 5 \times 10^6 \mathrm{cm}^{-6}\,\mathrm{pc}\left[\frac{S_\nu}{0.45\ \mathrm{mJy}}\right]\left[\frac{\theta_s}{0\rlap{.}''2}\right]^{-2}$. Assuming a characteristic scale $l/\mathrm{au} = (\theta_s/'')(d/\mathrm{pc}) \sim 83$ au, where $d = 414$ pc is the distance to Orion, the electron density of the plasma is $n_e \gtrsim 10^5\ \mathrm{cm}^{-3}\left[\frac{S_\nu}{0.45\ \mathrm{mJy}}\right]^{1/2}\left(\frac{\theta_s}{0\rlap{.}''2}\right)^{-3/2}$. The ejected plasma will recombine in a timescale $t_{\mathrm{rec}} = (n_e \alpha_2)^{-1} \lesssim 1$ year, where the recombination coefficient is $\alpha_2 = 2.6 \times 10^{-13}\ \mathrm{cm}^3\ \mathrm{s}^{-1}$. Assuming a proper motion of the ejecta $\mu \sim 60\ \mathrm{mas\ yr}^{-1}$, that corresponds in Orion to $120\ \mathrm{km\ s}^{-1}$, the crossing time is $t_{\mathrm{cross}} \sim l/v \sim 3$ year. Because $t_{\mathrm{cross}} > t_{\mathrm{rec}}$, one expects the plasma to recombine as it moves away from the source.[6]

Furthermore, if the ionized plasma is expanding, the density will drop. If the expansion is isotropic, the plasma volume is $V \propto l^3$ and the electron density will decrease like $n_e \propto l^{-3}$. For a jet condensation expanding with a fixed solid angle Ω, at a distance r from the source, the volume is $V \propto \Omega r^2 \Delta r$. If the size $\Delta r\sim$ constant, the volume will increase as $V \sim l^2$ and the electron density will decrease like $n_e \propto l^{-2}$. The optically thin radio flux density is $S_\nu \propto n_e^2 V$, and it will decrease like $S_\nu \propto l^{-3}$ in the isotropic case, and like $S_\nu \propto l^{-2}$ in the case of the jet condensation. Both types of flux density decrease were observed in the thermal radio jet HH 80–81 by Martí et al. (1998) who studied the evolution of two jet condensations. In any case, one expects that the observed radio emission of the ejection would decrease very fast both due to recombination and expansion of the ionized gas.

The assumption that we are dealing with optically thin free–free emission in the ejecta is supported by an analysis of the spectral index of source n in epoch 2012.76. Using the data of Forbrich et al. (2016) we obtain a total flux density of 1.45 ± 0.03 mJy at 7.3 GHz and of 1.68 ± 0.05 mJy at 4.7 GHz, This gives a spectral index of -0.3 ± 0.1, in agreement with Forbrich et al. (2016). For the southern component (the ejecta) we obtain flux densities of 0.45 ± 0.02 and 0.49 ± 0.03 at 7.3 and 4.7 GHz, respectively. This results in a spectral index of -0.2 ± 0.2, consistent with optically thin free–free-emission. Finally, for the northern component (proposed here to be the unresolved double stellar source) we obtain flux densities of 1.00 ± 0.02 and 1.19 ± 0.04 at 7.3 and 4.7 GHz, respectively. This gives a spectral index of -0.4 ± 0.1, suggesting a possible non-thermal component.

The total flux density of source n as a function of time (Figure 4) shows an important increment in epoch 2011.56. We believe that this increase (that has practically disappeared in more recent epochs) was the result of the ejection of the plasma cloud.

One can also estimate the mass-loss rate of an ionized jet, $\dot{M}_i = \Omega r^2 \mu \mathrm{m}_H n_e v \sim 3 \times 10^{-8}\left[\frac{S_\nu}{0.45\ \mathrm{mJy}}\right]^{1/2}\left[\frac{\theta_s}{0\rlap{.}''2}\right]^{1/2} M_\odot\ \mathrm{yr}^{-1}$. Assuming a jet ionization fraction $x_e \sim 0.1$, one obtains a total mass-loss rate $\dot{M} \sim 10^{-7}\ M_\odot\ \mathrm{yr}^{-1}$. This implies that source n must have an accretion disk with a healthy mass accretion rate, one order of magnitude larger, $\dot{M}_{\mathrm{acc}} \sim 10^{-6}\ M_\odot\ \mathrm{yr}^{-1}$ (e.g., Shu et al. 1993, p. 3).

Finally, Anglada et al. (2015) proposed a correlation between the radio luminosity of the jet, $S_{3.6\,\mathrm{cm}} d^2$, and the bolometric luminosity of the source, L_{bol} (their Equation (3)). Assuming a flat spectrum, this relation gives a luminosity $L \sim 44\ L_\odot$. From the observed IR fluxes from 5–10 μm (Gezari et al. 1998), one obtains a lower limit to the luminosity of source n, $L > 4\ L_\odot$.

The second way of testing the scenario is to verify that the proper motions derived for source n excluding the southern ejecta are consistent with the epoch of cluster disintegration, as determined from the well-behaved proper motions of sources BN and I. To pursue this test, in Table 2 we give the proper motions corrected for the mean proper motions of the Trapezium-BN/KL region ($\mu_\alpha \cos\delta = 1.07 \pm 0.09\ \mathrm{mas\ yr}^{-1}$; $\mu_\delta = -0.84 \pm 0.16\ \mathrm{mas\ yr}^{-1}$), as determined by Dzib et al. (2017). This relatively small correction is required to present the proper motions in the rest frame of Orion. In Figure 5 we present the position of the sources BN, I, and n as a function of time, as extrapolated from the proper motions in Table 2. The angle associated with each source represents the 2-σ error in the proper motions. We can see that the past positions of BN, I, and n overlap in the past both in right ascension as in declination. The data are consistent with a disintegration epoch during the 15th century with an initial position of $\alpha(J2000) = 05^{\mathrm{h}}35^{\mathrm{m}}14\rlap{.}^{\mathrm{s}}41; \delta(J2000) = -05°22'28\rlap{.}''2$. The more accurate determination using only the relative positions of BN and I gives a disintegration epoch of 1490 ± 11 (Gómez et al. 2008) and, with additional data points, of 1453 ± 9 (Goddi et al. 2011). With more data available, we will repeat below this determination.

[6] Nevertheless, if the ionized plasma is produced in a shock moving along the flow axis (e.g., faster wind reaching a slower upstream wind) the plasma would not recombine because it would be ionized in situ.

Table 2
Proper Motions Corrected to the Orion Frame and Deconvolved Dimensions of the Radio Sources

Name	Proper Motions[a]		Total Proper Motion[b]	Deconvolved Dimensions[c]
	$\mu_\alpha cos\delta$	μ_δ	Magnitude; PA	($\theta_{maj} \times \theta_{min}$; PA)
BN	−8.1 ± 0.4	+10.8 ± 0.4	13.5 ± 0.4; −37 ± 2	0″19 ± 0″01 × 0″07 ± 0″01; +58° ± 1°
n	+0.0 ± 0.9	−7.8 ± 0.6	7.8 ± 0.6; +180 ± 4	0″43 ± 0″01 × 0″17 ± 0″01; +16° ± 1°
I	+1.8 ± 0.4	−4.6 ± 0.4	4.9 ± 0.4; +159 ± 5	0″13 ± 0″01 × ⩽0″03 ± 0″01; +58° ± 3°

Notes.
[a] In mas yr^{-1}.
[b] Magnitude in mas yr^{-1}, PA in degrees.
[c] From the data of the Jansky VLA project SD0630 observed in epoch 2012.76 at the frequency of 7.3 GHz.

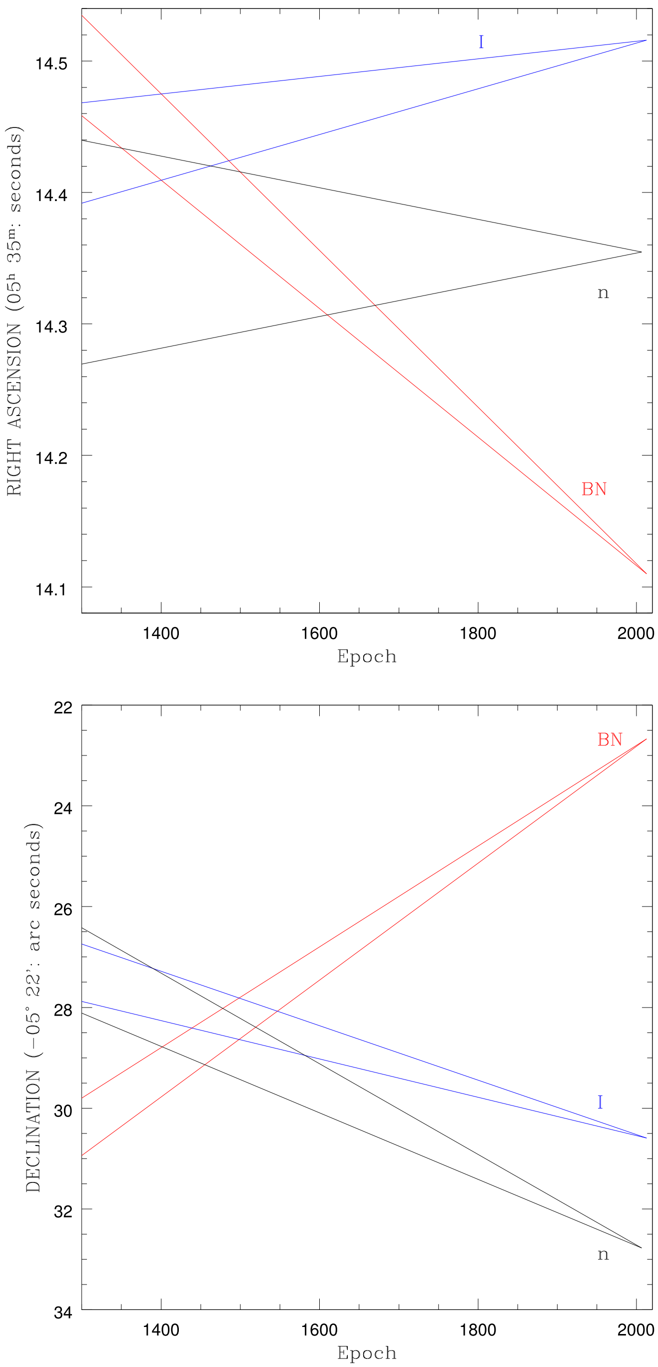

Figure 5. Proper motions of the sources BN (red), I (blue), and n (black) in the rest frame of Orion. The angles represent the ±2-σ error range in proper motions. The data are consistent with a disintegration epoch in the 1400–1500 period with an initial position of $\alpha(J2000) = 05^h35^m14^s.41$; $\delta(J2000) = -05°22'28''.2$.

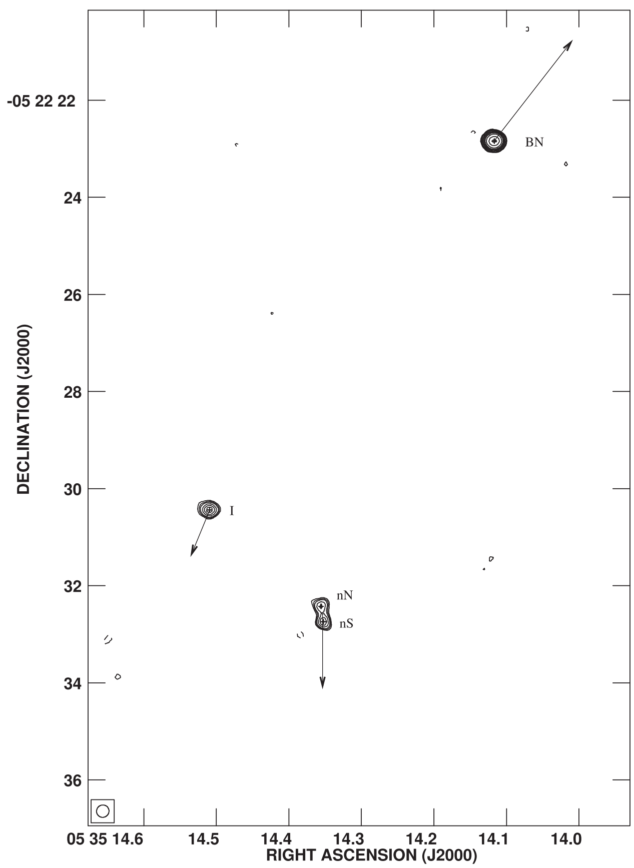

Figure 6. VLA 8.4 GHz continuum contour image of the BN/KL region for epoch 1991.67. The contours are −4, 4, 5, 6, 8, 10, 12, 15, 20, 30 and 40 times 88 μJy $beam^{-1}$, the rms noise of the image. The radio sources in the region are identified and the arrows indicate the proper motions in the frame of Orion for a period of 200 years. The half-power contour of the synthesized beam is shown in the bottom left corner (0″26 × 0″25; PA = −55°).

In Figure 6 we show the location of the three sources and, with arrows, the proper motions in the frame of Orion for a period of 200 years.

4. THE MINIMUM SEPARATION OF BN AND SOURCE I IN THE PAST

As discussed by Gómez et al. (2008), the minimum separation between BN and source I and when it took place in the past can be estimated accurately using relative astrometry between these two sources. This determination is very accurate because the relative astrometry is not affected by most of the error sources present in the absolute astrometry.

Table 3
VLA, Jansky VLA, and ALMA Data Used for the Determination of the Relative Proper Motions between BN and Source I

Epoch[a]	Project	λ (cm)	Synthesized Beam ($\theta_M \times \theta_m$; PA)[b]	$\Delta\alpha$[c] (s)	$\Delta\delta$[c] (arcsecs)
1985 Jan 19 (1985.05)	AM143	1.3	0."10 × 0."09; −7°	−0.38540 ± 0.00079	7.5123 ± 0.0128
1985 Jan 19 (1985.05)	AM143	2.0	0."16 × 0."13; +32°	−0.38550 ± 0.00074	7.5105 ± 0.0110
1986 Apr 28 (1986.32)	AC146	2.0	0."15 × 0."14; +10°	−0.38678 ± 0.00096	7.5202 ± 0.0133
1991 Sep 02 (1991.67)	AM335	1.3	0."10 × 0."10; −16°	−0.39143 ± 0.00074	7.5919 ± 0.0110
1994 Apr 29 (1994.33)	AM442	3.6	0."23 × 0."20; +1°	−0.39408 ± 0.00070	7.6425 ± 0.0108
1995 Jul 22 (1995.56)	AM494	3.6	0."26 × 0."32; +32°	−0.39422 ± 0.00079	7.6768 ± 0.0116
1996 Nov 21 (1996.89)	AM543	3.6	0."32 × 0."25; +0°	−0.39541 ± 0.00073	7.6988 ± 0.0117
1997 Jan 11 (1997.03)	AM543	3.6	0."33 × 0."25; −10°	−0.39471 ± 0.00078	7.7066 ± 0.0122
2000 Nov 10 (2000.86)	AM668	0.7	0."06 × 0."05; −25°	−0.39839 ± 0.00068	7.7309 ± 0.0102
2000 Nov 13 (2000.87)	AM668	3.6	0."24 × 0."22; +3°	−0.39898 ± 0.00078	7.7282 ± 0.0121
2002 Mar 31 (2002.25)	AG622	0.7	0."05 × 0."03; +25°	−0.40002 ± 0.00079	7.7541 ± 0.0131
2004 Nov 06 (2004.85)	AB1135	3.6	0."23 × 0."20; +1°	−0.40249 ± 0.00077	7.8079 ± 0.0120
2006 May 12 (2006.36)	AR593	3.6	0."26 × 0."22; −2°	−0.40426 ± 0.00077	7.8142 ± 0.0119
2007 Dec 14 (2007.95)	AR635	0.7	0."21 × 0."18; +20°	−0.40410 ± 0.00069	7.8365 ± 0.0105
2009 Jan 12 (2009.03)	AC952	0.7	0."08 × 0."05; +7°	−0.40511 ± 0.00063	7.8500 ± 0.0127
2011 Jun 04 (2011.42)	10B-175	0.9	0."14 × 0."09; −71°	−0.40618 ± 0.00031	7.8948 ± 0.0036
2011 Jul 02 (2011.50)	BL175	6.0	0."30 × 0."27; +46°	−0.40880 ± 0.00297	7.8981 ± 0.0243
2011 Jul 24 (2011.56)	BL175	6.0	0."47 × 0."24; −47°	−0.40779 ± 0.00250	7.9007 ± 0.0305
2011 Aug 29 (2011.66)	BL175	6.0	0."33 × 0."25; −30°	−0.40583 ± 0.00086	7.9039 ± 0.0139
2012 Oct 03 (2012.76)	SD0630	4.0	0."22 × 0."20; −7°	−0.40687 ± 0.00038	7.9154 ± 0.0058
2014 Mar 03 (2014.17)	13B-085	3.3	0."25 × 0."18; −38°	−0.40658 ± 0.00066	7.9521 ± 0.0135
2014 Mar 03 (2014.17)	13B-085	5.5	0."44 × 0."29; −38°	−0.40862 ± 0.00033	7.9425 ± 0.0053
2014 Jul 14 (2014.57)[d]	2012.1.00123.S	0.09	0."25 × 0."18; +66°	−0.40763 ± 0.00111	7.93152 ± 0.0136

Notes.
[a] The epochs used for the determination of the proper motions shown in Figures 1–3 are indicated in boldface.
[b] Major axis × minor axis in arcsec; PA in degrees.
[c] Positional offsets of BN with respect to source I in right ascension and declination.
[d] Data from the Atacama Large Millimeter Array (ALMA).

Following Gómez et al. (2008) we define as $x(t)$ and $y(t)$ the separations in right ascension and declination of BN with respect to source I as a function of epoch t and as μ_x and μ_y the proper motions in right ascension and declination.

The minimum separation takes place at an epoch $t_{\rm min}$ given by

$$t_{\rm min} = -\frac{x(2000.0)\mu_x + y(2000.0)\mu_y}{\mu_x^2 + \mu_y^2},$$

and this minimum separation is

$$s_{\rm min} = \frac{|x(2000.0)\mu_y - y(2000.0)\mu_x|}{(\mu_x^2 + \mu_y^2)^{1/2}}.$$

The least squares fit to 23 data points (14 from Gómez et al. 2008 and 9 from this paper) from the VLA, Jansky VLA, and Atacama Large Millimeter Array (ALMA) archives (shown in Table 3 and Figure 7) gives

$$x(2000.0) = -5.9385 \pm 0.0024 \text{ arcsec}, \quad \mu_x = -0.01133 \pm 0.00022 \text{ arcsec yr}^{-1},$$

$$y(2000.0) = 7.7282 \pm 0.0024 \text{ arcsec}, \quad \mu_y = 0.01472 \pm 0.00022 \text{ arcsec yr}^{-1}.$$

With these values, we obtain

$$t_{\rm min} = 1475 \pm 6,$$
$$s_{\rm min} = 0.''007 \pm 0.''093,$$

where the errors were calculated using standard propagation error theory (Wall & Jenkins 2003). The inclusion in this analysis of observations of different configurations and frequencies (and even different radio telescopes; one data point comes from ALMA) can affect the results. We argue, however, that both BN and source I are quite compact and that the determination of their centroids is not greatly affected by angular resolution, except in the sense that the precision of the astrometrical positions depends linearly with angular resolution but that this effect should not produce systematic shifts. As far as it is known, the sources do not present optical depth effects that could produce frequency-dependent displacements in the positions. Finally, as already noted above, the astrometry of this section is relative and this minimizes position shifts produced by the use of different complex gain calibrators. We conclude that, about 540 years ago, BN and source I were within less than $\sim$0."28 (3-σ upper limit) from each other in the plane of the sky. At a distance of 414 pc this corresponds to a physical separation of $\sim$120 au. We conclude that if by that epoch BN and/or source I had protoplanetary disks of typical dimensions (i.e., 100 au) the gas in these disks must have suffered a major disruption and could have originated the explosive molecular outflow present in the region. This result, however, poses a difficulty for the cluster disruption scenario as recently stressed by Plambeck & Wright (2016). These authors show, from ALMA observations, that at present source I has a disk with mass in the range of 0.02–0.2 $M_\odot$ and a diameter of $\sim$100 au. They note that such a massive

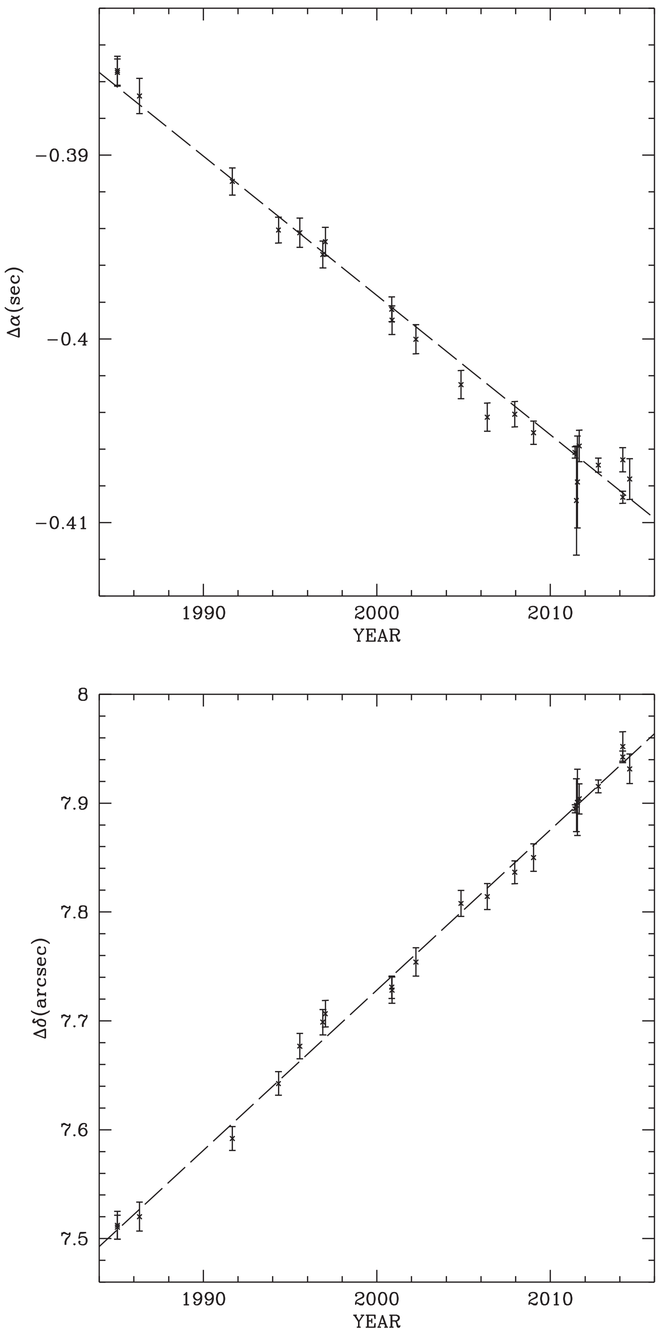

Figure 7. Proper motions of BN with respect to source I for right ascension (top) and declination (bottom). The dashed lines represent the least-squares fits to the data.

disk could not have formed in only 500 years from Bondi–Hoyle accretion (gravitational focusing) as source I moves in the dense ($\sim 10^7$ cm^{-3}) ambient medium of the BN/KL region. However, Goddi et al. (2011) have pointed out that if source I existed as a softer binary before the close encounter this could have enabled preservation of the original accretion disk, although truncated to its present radius of ~50 au. The numerical analysis of Moeckel & Goddi (2012) confirms to first order the plausibility of the scattering scenario of Goddi et al. (2011) and suggests that the original disk was largely preserved. There is still much to understand of the explosive phenomena present in BN/KL.

5. CONCLUSIONS

The analysis of archive VLA data as well as new high sensitivity Jansky VLA observations allowed a new improved determination of the proper motions of the stellar sources BN, I, and n in the Orion BN/KL region. The proper motions of sources BN and I are consistent with previous measurements in the literature and a ballistic nature. The proper motions of the double source n are complicated by the appearance of a new component, most likely a cloud of ionized gas that was ejected from one of the stars in source n after 2006.36. We estimate that this cloud is moving at velocities of more than 120 km s^{-1} in the plane of the sky. The proper motions of BN, I, and n are consistent with a disintegration epoch in the 15th century. Finally, we used the relative proper motions between sources BN and I to accurately determine that the closest separation took place in the year 1475 $\pm$ 6, when they were within 110 au or less from each other in the plane of the sky.

This research has made use of the SIMBAD database, operated at CDS, Strasbourg, France. L.F.R. and L.L. are grateful to CONACyT, Mexico and DGAPA, UNAM for their financial support. S.L. acknowledges support from project DGAPA IN105815 and CONACytT 238631. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2012.1.00123.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada) and NSC and ASIAA (Taiwan), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO, and NAOJ.

REFERENCES

Anglada, G., Rodríguez, L. F., & Carrasco-González, C. 2015, in Advancing Astrophysics with the Square Kilometre Array, The Cradle of Life (Trieste: SISSA), 121
Bally, J., Ginsburg, A., Silvia, D., & Youngblood, A. 2015, A&A, 579, A130
Bally, J., & Zinnecker, H. 2005, AJ, 129, 2281
Codella, C., Maury, A. J., Gueth, F., et al. 2014, A&A, 563, L3
Dzib, S. A., Loinard, L., Rodriguez, L. F., et al. 2017, ApJ, 834, 139
Forbrich, J., Rivilla, V. M., Menten, K. M., et al. 2016, ApJ, 822, 93
Gezari, D. Y., Backman, D. E., & Werner, M. W. 1998, ApJ, 509, 283
Goddi, C., Humphreys, E. M. L., Greenhill, L. J., Chandler, C. J., & Matthews, L. D. 2011, ApJ, 728, 15
Gómez, L., Rodríguez, L. F., & Loinard, L. 2013, RMxAA, 49, 79
Gómez, L., Rodríguez, L. F., Loinard, L., et al. 2008, ApJ, 685, 333
Hull, C. L. H., Girart, J. M., Kristensen, L. E., et al. 2016, ApJL, 823, L27
Kounkel, M., Hartmann, L., Loinard, L., et al. 2016, ApJ, in press
Martí, J., Rodríguez, L. F., & Reipurth, B. 1998, ApJ, 502, 337
Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, A&A, 474, 515
Moeckel, N., & Goddi, C. 2012, MNRAS, 419, 1390
Plambeck, R. L., & Wright, M. C. H. 2016, arXiv:1608.00996
Rodríguez, L. F., Dzib, S. A., Loinard, L., et al. 2012a, RMxAA, 48, 243
Rodríguez, L. F., González, R. F., Raga, A. C., et al. 2012b, A&A, 537, A123
Rodríguez-Kamenetzky, A., Carrasco-González, C., Araudo, A., et al. 2016, ApJ, 818, 27
Shu, F., Najita, J., Galli, D., Ostriker, E., & Lizano, S. 1993, in Protostars and Planets III, ed. E. H. Levy & J. I. Lunine (Tucson, AZ: Univ. of Arizona Press), 3
Wall, J. V., & Jenkins, C. R. 2003, Practical Statistics for Astronomers, vol. 3 (Cambridge: Cambridge Univ. Press)
Youngblood, A., Ginsburg, A., & Bally, J. 2016, AJ, 151, 173
Zapata, L. A., Ho, P. T. P., Rodríguez, L. F., et al. 2006, ApJ, 653, 398
Zapata, L. A., Schmid-Burgk, J., Ho, P. T. P., Rodríguez, L. F., & Menten, K. M. 2009, ApJL, 704, L45