RESOLVING THE STRUCTURE AND KINEMATICS OF THE BN OBJECT AT 0\arcsec2 RESOLUTION

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ABSTRACT

We present sensitive 7 mm observations of the H53\(\alpha\) recombination line and adjacent continuum, made toward the Orion BN/KL region. In the continuum we detect the BN object, the radio source I (GMR I) and the radio counterpart of the infrared (IR) source n (Orion-n). Comparing with observations made at similar angular resolutions but lower frequency, we discuss the spectral indices and angular sizes of these sources. In the H53\(\alpha\) line, we only detect the BN object. This is the first time that radio recombination lines have been detected from this source. The LSR radial velocity of BN from the H53\(\alpha\) line, \(v_{\text{LSR}} = 20.1 \pm 2.1 \text{ km s}^{-1}\), is consistent with that found from previous studies in near-IR lines. While the continuum emission is expected to have considerable optical depth at 7 mm, the observed H53\(\alpha\) line emission is consistent with an optically thin nature and we discuss possible explanations for this apparent discrepancy. There is evidence of a velocity gradient, with the NE part of BN being redshifted by \(\sim 10 \text{ km s}^{-1}\) with respect to the SW part. This is consistent with the suggestion of Jiang et al. that BN may be driving an ionized outflow along that direction.

Key words: ISM: individual (Orion) – radio continuum: ISM – radio lines: ISM

1. INTRODUCTION

Located at about 1\arcmin to the NW of the Orion Trapezium, the BN/KL region has been, as the closest region of massive star formation, the subject of extensive studies. 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 \(\text{km s}^{-1}\)) for the radio sources associated with the infrared (IR) sources BN 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 point where they must all have been located about 500 years ago. Even with these proper motions now available, there is no radial velocity information for these three sources, with the exception of the near-IR spectroscopic study of BN made by Scoville et al. (1983) that reports an LSR radial velocity of \(+21 \text{ km s}^{-1}\) for this source. In this paper, we present 7 mm continuum and H53\(\alpha\) radio recombination line observations of the BN/KL region in an attempt to obtain additional information on the radial velocities of these sources.

2. OBSERVATIONS

The 7 mm observations were made in the B configuration of the VLA of the NRAO, during 2007 December 14. The central rest frequency observed was that of the H53\(\alpha\) line, 42951.97 MHz, and we integrated on-source for a total of approximately 3 hr. The observations were made using the spectral line mode, with 15 channels of 1.56 MHz each (10.9 km s\(^{-1}\)) and averaging both circular polarizations. The bandpass calibrator was 0319 + 415. A continuum channel recorded the central 75% of the full spectral window. The absolute amplitude calibrator was 1331+305 (with an adopted flux density of 1.47 Jy) and the phase calibrator was 0541 – 056 (with a bootstrapped flux density of 1.78 ± 0.08 Jy). The phase noise root mean square (rms) was about 30\(^{\circ}\), indicating good weather conditions. The phase center of these observations was at \(\alpha(2000) = 05^h 35^m 14.13^s; \delta(2000) = -05^\circ 22^\prime 26^\prime\prime\).

The data were acquired and reduced using the recommended VLA procedures for high-frequency data, including the fast-switching mode with a cycle of 120 s. Clean maps were obtained using the task IMAGR of AIPS with the ROBUST parameter set to 0.

3. CONTINUUM ANALYSIS

3.1. Spectral Indices

In Figure 1, we show the image obtained from the continuum channel. Three sources, BN, I, and n, are evident in the image. No other sources were detected above a 5\(^{\sigma}\) lower limit of 1.75 mJy in our 1\arcmin field of view. The positions, flux densities, and deconvolved angular sizes of these sources are given in Table 1. The continuum flux density of the sources has been obtained from the line-free channels. The line emission will be discussed below. The flux density obtained at 7 mm by us for BN is in good agreement with the values previously reported in the literature: we obtain a flux density of 28.6 ± 0.6 mJy, while values of 31.5 ± 5 and 28.0 ± 0.6 were obtained by Menten & Reid (1995) and Chandler & Wood (1997), respectively. In the case of source I, the agreement is acceptable, since we obtain a flux density of 14.5 ± 0.7 mJy, while values of 13 ± 2 and 10.8 ± 0.6 mJy were reported by Menten & Reid (1995) and Chandler & Wood (1997), respectively. Careful monitoring would be required to test if the radio continuum from source I is variable in time.

The spectral indices determined from our 7 mm observations and the 3.6 cm observations of Gómez et al. (2008) are given in the last column of Table 2. Our spectral indices for BN and I are in excellent agreement with the more detailed analysis presented by Plambeck et al. (1995) and Beuther et al. (2004).
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Table 1
Parameters of the 7 mm Continuum Sources in the Orion BN/KL Region

| Source | Position* | Total Flux | Deconvolved Angular Sizeb |
|--------|-----------|------------|----------------------------|
|        | α(J2000)  | δ(J2000)   | Density (mJy)              |                           |
| BN     | 05 35 14.110 | −05 22 22.73 | 28.6 ± 0.6 | 0.07 ± 0.01 × 0.05 ± 0.01; +45° ± 29° |
| n      | 05 35 14.359 | −05 22 32.78 | 3.0 ± 0.6 | ≤ 0'2 |
| I      | 05 35 14.514 | −05 22 30.57 | 14.5 ± 0.7 | 0.09 ± 0.01 × 0.06 ± 0.02; +134° ± 44° |

Notes.
* 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.
* Major axis × minor axis; position angle of the major axis.

Table 2
Parameters of the 3.6 cm Continuum Sources in the Orion BN/KL Region

| Source | Position* | Total Flux | Deconvolved Angular Sizeb | Spectral Index |
|--------|-----------|------------|----------------------------|---------------|
|        | α(J2000)  | δ(J2000)   | Density (mJy)              |               |
| BN     | 05 35 14.110 | −05 22 22.74 | 4.8 ± 0.1 | 0.17 ± 0.01 × 0.08 ± 0.02; +63° ± 7° |
| n      | 05 35 14.355 | −05 22 32.78 | 2.2 ± 0.2 | 0.50 ± 0.03 × ≤ 0'09; +20° ± 3° |
| I      | 05 35 14.514 | −05 22 30.56 | 1.2 ± 0.1 | 0.19 ± 0.04 × ≤ 0'15; +13° ± 23° |

Notes.
* 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.
* Major axis × minor axis; position angle of the major axis.

Figure 1. Contour image of the 7 mm continuum emission from the BN/KL region. The three sources detected are marked with their names. Contours are −5, 5, 10, 20, and 40 times 0.35 mJy beam−1, the rms noise of the image. The half power contour of the synthesized beam (0.17 × 0.15 with a position angle of +17°) is shown in the bottom-left corner.

We have detected source n for the first time at 7 mm and this detection allows the first estimate of the spectral index of this source over a wide frequency range. The value of 0.2 ± 0.1 suggests marginally thick free–free emission, as expected in an ionized outflow. This supports the interpretation of this source as an ionized outflow by Gómez et al. (2008). The position given by us in Table 1 is consistent with the extrapolation of the proper motions of this source discussed by Gómez et al. (2008).

3.2. Deconvolved Angular Sizes

The radio source I has parameters consistent with an optically thick free–free source (with a spectral index of 1.5 ± 0.1). Beuther et al. (2004) suggest that this spectral index is either the result of optically thick free–free plus dust emission, or H− free–free emission that gives rise to a power-law spectrum with an index of ∼1.6.

In the case of the radio source associated with the IR source n we only have an upper limit to its size at 7 mm. In addition, Gómez et al. (2008) report important morphological variations over time in this source that suggest that comparisons at different frequencies should be made only from simultaneous observations.

In the case of BN, the frequency dependences of flux density and angular size (this last parameter taken to be the geometric mean of the major and minor axes reported in Tables 1 and 2) can be accounted for with a simple model of a sphere of ionized gas in which the electron density decreases as a power-law function of radius, ne ∝ r−α. In this case, the flux density of the source is expected to go with frequency as Sν ∝ ν2α/(1−2α) (Reynolds 1986). The frequency dependences of flux density (Sν ∝ ν1.1±0.1) and angular size (θν ∝ ν−0.36±0.12) for BN are consistent with a steeply declining electron density distribution with a power-law index of α = 3.0 ± 0.3. The continuum spectrum of BN produced by Plambeck et al. (1995) indicates that a constant spectral index extends from 5 to 100 GHz.

4. ANALYSIS OF THE H53α RECOMBINATION LINE EMISSION

4.1. Radial LSR Velocity

We clearly detected the H53α line emission only from BN. The spectrum is shown in Figure 2. The parameters of the
and not from BN. In LTE, the electron temperature, $T_e$, is given by (Mezger & Högland 1967; Gordon 1969; Quireza et al. 2006)

$$ T_e = \frac{7100 \left( \frac{\nu_L}{\text{GHz}} \right)^{1.1} \left( \frac{S_C}{S_L} \right) \left( \frac{\Delta \nu}{\text{km s}^{-1}} \right)^{-1} (1+y^+)^{-1}}{\frac{1.87}{0.87}}, $$

where $\nu_L$ is the line frequency, $S_C$ is the continuum flux density, $S_L$ is the peak line flux density, $\Delta \nu$ is the FWHM line width, and $y^+$ is the ionized helium to ionized hydrogen abundance ratio. In the case of BN, we can adopt $y^+ \approx 0$ given that the source is not of very high luminosity, and using the values given in Tables 1 and 3 we obtain $T_e^* \approx 8200$ K. This value is similar to that determined for the nearby Orion A from radio recombination lines (e.g., Lichten et al. 1979).

It is somewhat surprising that we get a very reasonable estimate for $T_e^*$ when our previous discussion seemed to imply that BN is partially optically thick at 7 mm. One possibility is that we have two effects fortuitously canceling each other. For example, the optical thickness of the source will diminish the line emission, while maser effects (such as those observed in MWC 349; Martín-Pintado et al. 1989) will amplify the line. However, in an attempt to understand this result in LTE conditions, we will discuss the expected LTE radio recombination line emission from a sphere of ionized gas in which the electron density decreases as a power-law function of radius, $n_e \propto r^{-\alpha}$. As noted before, the modeling of the continuum emission from such a source was presented in detail by Panagia & Felli (1975) and Reynolds (1986). The radio recombination line emission for the case $\alpha = 2$ has been discussed by Altenhoff et al. (1981) and Rodríguez (1982). Here, we generalize the derivation of the recombination line emission to the case of $\alpha > 1.5$. This lower limit is adopted to avoid the total emission from the source to diverge.

For a sphere of ionized gas, the free–free continuum emission will be given by (Panagia & Felli 1975)

$$ S_C = 2\pi \frac{r_0^2}{d^2} B_0 \int_0^\infty (1 - \exp[-\tau_C(\xi)]) \xi d\xi, $$

where $r_0$ is a reference radius, $d$ is the distance to the source, $B_0$ is Planck’s function, $\xi$ is the projected radius in units of $r_0$, and $\tau_C(\xi)$ is the continuum optical depth along the line of sight with projected radius $\xi$. On the other hand, the free–free continuum plus radio recombination line emission will be given by an equation similar to Equation (2), but with the continuum opacity substituted by the continuum plus line opacity (Rodríguez 1982):

$$ S_{L+C} = 2\pi \frac{r_0^2}{d^2} B_0 \int_0^\infty (1 - \exp[-\tau_{L+C}(\xi)]) \xi d\xi, $$

where $\tau_{L+C}(\xi)$ is the line plus continuum optical depth along the line of sight with projected radius $\xi$.

The line-to-continuum ratio will be given by

$$ \frac{S_L}{S_C} = \frac{S_{L+C} - S_C}{S_C}. $$

The opacity of these emission processes depends on the projected radius as (Panagia & Felli 1975)

$$ \tau(\xi) \propto \xi^{-(2\alpha-1)}. $$

We now introduce the definite integral (Gradshteyn & Ryzhik 1994)

$$ \int_0^\infty (1 - \exp[-\mu x^{-p}]) x dx = -\frac{1}{p} \mu^\frac{\Gamma\left(-\frac{2}{p}\right)}{\Gamma\left(1-\frac{1}{p}\right)}, $$

valid for $\mu > 0$ and $p > 0$ and with $\Gamma$ being the Gamma function. Substituting Equations (2) and (3) in Equation (4), and using the integral defined in Equation (7), it can be shown that

$$ \frac{S_L}{S_C} = \left(\frac{\kappa_L + \kappa_C}{\kappa_C}\right)^{1/(\alpha-0.5)} - 1, $$

Table 3

| Peak Flux (mJy) | Half Maximum Line Width (km s$^{-1}$) | LSR Radial Velocity (km s$^{-1}$) |
|-----------------|--------------------------------------|----------------------------------|
| 10.4 ± 1.1      | 39.0 ± 4.9                           | 20.1 ± 2.1                       |

Figure 2. Spectrum of the H53α line emission from BN. The dashed line is the least-squares fit to the data, whose parameters are given in Table 3.
where $\kappa_L$ and $\kappa_C$ are the line and continuum absorption coefficients at the frequency of observation, respectively. In this last step we have also assumed that the opacities of the line and continuum processes are proportional to the line and continuum absorption coefficients, respectively, that is, that the physical depths producing the line and continuum emissions are the same. Under the LTE assumption, we have that

$$\frac{\kappa_L}{\kappa_C} = \frac{7100}{\nu} \left( \frac{T_e}{K} \right)^{-1.1} \left( \frac{\Delta \nu}{\text{km s}^{-1}} \right)^{-1} (1 + y^*)^{-1}. \quad (8)$$

For $\nu \leq 43$ GHz and typical parameters of an H II region, we can see from Equation (8) that $\kappa_L < \kappa_C$, and Equation (7) can be approximated by

$$\frac{S_L}{S_C} \approx \frac{1}{\alpha - 0.5} \left( \frac{\kappa_L}{\kappa_C} \right). \quad (9)$$

That is, the expected optically thin, LTE line-to-continuum ratio,

$$\frac{S_L}{S_C} \approx \left( \frac{\kappa_L}{\kappa_C} \right), \quad (10)$$

becomes attenuated by a factor $1/(\alpha - 0.5)$. In the case of $\alpha = 2$, the factor is $2/3$, and we reproduce the result of Altenhoff et al. (1981) and Rodríguez (1982). In the case of BN, we have that $\alpha \simeq 3$, and we expect the attenuation factor to be
2/5. If BN can be modeled this way, we would have expected to derive electron temperatures under the LTE assumption (see Equation (1)) of order

\[ T_e^* (\alpha = 3) \simeq 2.2T_e^* \text{ (thin)}. \tag{11} \]

However, from the discussion in the first paragraph of this section observationally we determine that

\[ T_e^* (\alpha = 3) \simeq T_e^* \text{ (thin)}. \tag{12} \]

Summarizing, (i) BN seems to have significant optical depth in the continuum at 7 mm, (ii) this significant optical depth should attenuate the observed recombination line emission with respect to the optically thin case, but (iii) the line emission seems to be as strong as in the optically thin case.

As possible explanations for the “normal” (apparently optically thin and in LTE) radio recombination line emission observed from BN we can think of two options. The first is that, as noted before, there is a non-LTE line-amplifying mechanism that approximately compensates for the optical depth attenuation. The second possibility is that the free–free emission from BN at 7 mm is already optically thin. However, this last possibility seems to be in contradiction with the results of Plambeck et al. (1995) that suggest a single spectral index from 5 to 100 GHz. Observations of radio recombination lines around 100 GHz are needed to solve this problem.

A comparison with the H53α emission from the hypercompact H II region G28.20-0.04N is also of interest. The continuum flux densities from this source at 21, 6, 3.6, and 2 cm are 49, 135, 297, and 543 mJy, respectively (Sewilo et al. 2004). At 7 mm the continuum flux density is 641 mJy (Sewilo et al. 2008), indicating that the source has become optically thin at this wavelength. Using the H53α line parameters given by Sewilo et al. (2008) we derive an LTE electron temperature of \( T_e^* \simeq 7600 \text{ K} \), similar to the value for BN and in this case consistent with the optically thin nature of G28.20-0.04N.

The nondetection of H53α emission from radio source I is consistent with its expected large optical depth. The formulation above implies \( \alpha \simeq 5 \), and an attenuation factor of 2\(^{-\alpha} \). This confirms the notion that BN and radio source I are two sources intrinsically very different in nature. This difference is also evident in the brightness temperature of both sources. At 7 mm, the brightness temperature of a source is

\[ \frac{T_B}{K} \simeq 0.96 \left[ \frac{S_{\nu}}{\text{mJy}} \right] \left[ \frac{\theta_{\text{maj}} \times \theta_{\text{min}}}{\text{arcsec}^2} \right]^{-2}. \tag{13} \]

Using the values of Table 1, we get \( T_B \simeq 7800 \text{ K} \) for BN, confirming its nature as photoionized gas. However, for the radio source I we get \( T_B \simeq 2600 \text{ K} \). So, even when source I seems to be optically thick, its brightness temperature is substantially lower than that expected for a photoionized region. Reid et al. (2007) have discussed as possible explanations for this low brightness temperature H\(^-\) free–free opacity or a photoionized disk.

Following the discussion of Reid et al. (2007), we consider it unlikely that dust emission could be a dominant contributor to the 7 mm emission of BN or Orion I. A dense, warm, dusty disk would be expected to show many molecular lines at millimeter/submillimeter wavelengths. While Beuther et al. (2006) and Friedel & Snyder (2008) find numerous, strong, molecular lines toward the nearby “hot core,” they find no strong lines toward the position of Orion I (with the exception of the strong SiO masers slightly offset from Orion I) or BN. Also, the brightness temperatures derived by us at 7 mm (7800 K for BN and 2600 K for source I) are high enough to sublimate dust and suggest that free–free emission from ionized gas dominates the continuum emission. Finally, the continuum spectra of BN and of source I, measured by Plambeck et al. (1995) and Beuther et al. (2006), respectively, suggest that the dust emission becomes dominant only above \( \sim 300 \text{ GHz} \).

In the case of source n, no detection was expected given its weakness even in the continuum.

4.3. Spatial Distribution of the H53α Line Emission

The H53α line emission in the individual velocity channels shows evidence of structure but unfortunately the signal-to-noise ratio is not large enough to reach reliable conclusions from the analysis of these individual channels. However, an image with good signal-to-noise ratio can be obtained averaging over the velocity range of \(-21.2 \text{ to } +66.1 \text{ km s}^{-1}\), using the task MOMNT in AIPS. This line image is compared in Figure 3 with a continuum image made from the line-free channels. The larger apparent size of the continuum image is simply the result of its much better signal-to-noise ratio. For the total line emission we obtain an upper limit of 0′.12 for its size that is consistent with the size of the continuum emission given in Table 1. We also show images of the blueshifted \((-21.2 \text{ to } +22.5 \text{ km s}^{-1}\) and redshifted \(+22.5 \to +66.1 \text{ km s}^{-1}\) line emission in Figure 3. The cross in the figure indicates the centroid of the total line emission. The centroid of the line emission does not appear to coincide with the centroid of the continuum emission and we attribute this to opacity effects.

An interesting conclusion comes from comparing the total line emission with the blueshifted and redshifted components. The blueshifted emission seems slightly shifted to the SW, while the redshifted emission seems slightly shifted to the NE, suggesting a velocity gradient. This result supports the suggestion of Jiang et al. (2005) of the presence of an outflow in BN along a position angle of 36°. Given the modest signal-to-noise ratio of the data, it is difficult to estimate the magnitude of the velocity shift and we crudely assume that it is of order one channel \((\sim 10 \text{ km s}^{-1}\), since most of the line emission is concentrated in the central two channels of the spectrum (see Figure 2). The position shift between the blueshifted and redshifted emissions is 0′.028 \(\pm 0′.007 \text{ (12} \pm 3 \text{ AU at the distance of 414 pc given by Menten et al. (2007)), significant to the 4σ level. Unfortunately, the data of Jiang et al. (2005) do not include line observations and there is no kinematic information in their paper to compare with our results. The small velocity gradient observed by us in BN is consistent with a slow bipolar outflow but also with Keplerian rotation around a central mass of only \(0.2 M_\odot\).

5. CONCLUSIONS

We have presented observations of the H53α recombination line and adjacent continuum toward the Orion BN/KL region. In the continuum we detect the BN object, the radio source I (GMR I), and the radio counterpart of the IR source n (Orion-n), and discuss its parameters. In the H53α line we only detect the BN object, the first time that radio recombination lines have been detected from this source. The LSR radial velocity of BN from the H53α line, \( v_{\text{LSR}} = 20.1 \pm 2.1 \text{ km s}^{-1}\), is consistent with that found from previous studies in near-IR lines,
\( v_{\text{LSR}} = 21 \, \text{km s}^{-1} \). We discuss the line-to-continuum ratio from BN and present evidence for a possible velocity gradient across this source.

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