THE NON-THERMAL RADIO JET TOWARD THE NGC 2264 STAR FORMATION REGION

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ABSTRACT

We report sensitive VLA 3.6 cm radio observations toward the head of the Cone Nebula in NGC 2264, made in 2006. The purpose of these observations was to study a non-thermal radio jet recently discovered, which appears to emanate from the head of the Cone Nebula. The jet is highly polarized, with well-defined knots, and one-sided. Comparison of our images with 1995 archive data indicates no evidence of proper motions or polarization changes. We find reliable flux density variations in only one knot, which we tentatively identify as the core of a quasar or radio galaxy. An extragalactic location seems to be the best explanation for this jet.

Key words: galaxies: jets – radiation mechanisms: non-thermal – radio continuum: galaxies

Online-only material: color figure

1. INTRODUCTION

Reipurth et al. (2004) searched for radio continuum emission from proto-stellar objects in eight regions of star formation. In the NGC 2264 region they discovered a remarkably collimated radio jet, less than 1’ away from the head of the well-known Cone Nebula and apparently emanating from it (see Figure 1). Furthermore, the total flux density of the jet at 3.6 cm is ~11 mJy, and the a priori probability of finding a background source with this flux density in a region of 2’ × 2’ is only 0.0004 (Windhorst et al. 1993), suggesting a possible association between the jet and the Cone Nebula.

The Cone Nebula, discovered in 1784 by William Herschel, is believed to be a pillar of gas and dust whose head is most probably externally ionized by S Mon, a massive O-type binary (Gies et al. 1997) located about 30’ to the north of the nebula. The head of the Cone Nebula is a dense (~10^4 cm^-3) molecular core with an estimated mass of 16 M⊙ (Pagani & Nguyen-Q-Rieu 1987). The position where the jet is located has one of the highest surface densities of T Tau stars in the region (Dahm & Simon 2005). These circumstances suggested that the radio jet could be physically associated with a young stellar object in the region. Spectacular optical jets emanating from the head of dust pillars have been found in the Trifid (e.g. Yusef-Zadeh et al. 2005) and in Carina (http://antwrp.gsfc.nasa.gov/apod/ap070430.html).

The overall extent of the jet is about 28”, and (with subarcsec resolution) it seems to be composed of eight knots. Reipurth et al. (2004) found that, assuming that the jet was in the NGC 2264 region (at a distance of 760 pc; Sung et al. 1997) and that the knots were moving with a velocity of 100 km s^-1 in the plane of the sky, an ejection every 60 years was implied. This timescale is consistent with that found for knots in jets associated with young stellar objects (e.g. Curiel et al. 1993).

On the other hand, due to the non-thermal nature of its emission and that the jet also presents a high degree of polarization, Reipurth et al. (2004) concluded that these characteristics were consistent with an extragalactic jet. The authors found no obvious counterparts in the IRAS catalogs or at 2.2 μm emission, nor with HST observations. A search in the SIMBAD database shows only two stars: V367 Mon and NGC 2264 LBM 6255 (Lamm et al. 2005) in the region of the jet, but neither clearly associated with any of the knots (see Figure 1).

In this work we report an analysis of this jet, using both new as well as archive Very Large Array (VLA) radio data. Our main goal was to compare images taken at two different epochs to search for proper motions and variability that could allow us to favor a galactic or an extragalactic nature for the jet. For example, the presence of large proper motions in the knots would favor a galactic location. We first searched for 3.6 cm data in the VLA archive and found three epochs (1990, 1995, and 2002) where the source was included in the primary beam of the observations. These data did not prove appropriate for a reliable search for proper motions and variability because they have different wavelengths, pointing centers, and phase calibrators. In order to make a reliable, high-precision comparison we made new VLA observations in 2006 that match...
2. OBSERVATIONS

Our new observations were made with the NRAO\textsuperscript{1} Very Large Array, in the B configuration at a wavelength of 3.6 cm, on 2006 September 7 (we will refer to the epoch of these data, taken under VLA project code AR599, as 2006.68). These data have an on-source integration time of 4.9 h. The 1995 December 16 (epoch 1995.96 taken under VLA project code AW420) data have, as we noted before, the same observational parameters and have an on-source integration time of 3.4 h. The $uv$ coverage of both data sets is roughly the same, even when the 2006 data had two antennas missing at the center of two of the arms at the time of the observations.

To obtain two images for reliable comparison we convolved both images to the same angular resolution, resulting in a beam with a half power full width of 0.86'. These images were made with the ROBUST parameter of the task IMAGR set to 0.

The absolute amplitude calibration accuracy of the images is uncertain at the $\sim$10\% level. However, due to the good $uv$ coverage, the relative strength of features in an individual image is measured to higher accuracy. Thus, to allow a direct comparison of these data taken with a time separation of 10.72 years.

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comparison of the images, we have solved for a relative scale factor which brings the two images into best agreement. Specifically, we combined the images (subtracting the 1995.96 image from the 2006.68 image) in order to get the smallest rms value in the difference image. The final factor for scaling was multiplying the 1995.96 image by 0.93. In the following section we present and discuss these images.

To gain a better understanding of the region as a whole, we searched in the VLA archive for radio continuum observations of lower angular resolution than those discussed here. For the epoch 1984 August 31 we found observations taken at 6 cm under VLA project code AS204 in the D configuration (angular resolution of $\sim 15''$). These observations have been published and discussed by Schwartz et al. (1985), and our conclusions, discussed below, confirm their interpretation. These data were reduced following the standard VLA procedures.

3. RESULTS AND DISCUSSION

We looked for flux density and degree-of-polarization variations as well as proper motions between the 1995 and 2006 images. In Figure 2 we show the continuum emission from both epochs as well as the difference image (2006–1995).

3.1. Flux Density Variations and Search for Proper Motions

The difference image shows no significant variation in the flux density at a 5σ level of 0.1 mJy, except for one of the knots, located at $\alpha(2000) = 06^h41^m15^s60, \delta(2000) = 09^\circ26'45''774$, that we identify as the nucleus of the source. In contrast, none of the other knots shows variation above the 5σ level of 0.1 mJy, which implies upper limits to any variability in the range of 3–15%, according to their flux density.

We also searched for proper motions in the knots, setting typical 3σ upper limits of 1.6 mas yr$^{-1}$. If the source was located at the distance of NGC 2264, these upper limits would imply 3σ upper limits of 5.8 km s$^{-1}$ for the motion in the plane of the sky. Knots in outflows associated with star formation regions are known to move at velocities in the range of 100–500 km s$^{-1}$ (Rodríguez et al. 1989; Curiel et al. 2006). In the case of galactic microquasars (Mirabel & Rodríguez 1999), the velocities are much larger, comparable to the speed of light. We conclude that the observed lack of flux density variations and, in particular, the stringent upper limits to any proper motions argue strongly against a galactic nature for this jet.

As mentioned before, the only knot that is found to be variable in flux density most probably traces the nucleus of this extragalactic jet. This component increased its flux density from $2.3 \pm 0.1$ to $3.7 \pm 0.1$ mJy over the period of the observations.

3.2. Linear Polarization

On the other hand, the jet presents highly polarized emission, in some knots up to 30% (see Figure 3), including the single knot (most probably a lobe) seen to the west (see Figure 4). One important fact is the absence of detectable polarized emission in the knot presenting variations in flux density (see Figure 3). This supports the idea that this knot is probably the core of a quasar or radio galaxy, which are known to be rapidly variable and to show a small degree of linear polarization, of order 1% (Saikia & Kulkarni 1998). Figure 3 shows that the magnetic field is almost parallel to the jet along most of its extension, except in the final knot where it turns to be almost perpendicular. This polarization behavior is similar in orientation and percentage to that observed in the jet of the well-known quasar 3C 273 (Conway et al. 1993).

Due to the ratio of the fluxes of both sides of the jet, we classified this jet as being one-sided, applying the rules given by Bridle & Perley (1984) and Fanaroff & Riley (1974). This jet seems to be also of type FR II, but the classification implies bright hot spots in the outer regions, which are not present in this jet.

3.3. Large Scale Radio Emission

An image of the VLA archive data is shown in Figure 5. This image is superimposed on the STScI Digitized Sky Survey (DSS) red image for the same region. From this overlay, we can see that the Cone Nebula is associated with two types of radio emission. The compact double source to its NE is the radio jet discussed here. The more diffuse radio emission associated with the optical emission from the head and the “shoulder” of the Cone is most likely free–free emission from gas photoionized by S Mon, the massive O-type binary located about 30′ to the north of the nebula. This diffuse radio emission has a total flux density of $\sim 10$ mJy. If we assume that it is coming from optically thin free–free emission at an electron temperature of $10^4$ K, and that the region is located at a distance of 760 pc, an ionizing photon rate of $5 \times 10^{44}$ s$^{-1}$ is required. Furthermore, assuming that the region of diffuse free–free emission subtends an angular diameter of 1’ with respect to the angular separation of 30′ from S Mon, a solid angle correction factor of $1.4 \times 10^3$ gives a total ionizing photon rate of $7 \times 10^{48}$ s$^{-1}$ for S Mon. This is consistent with the rate expected from an O7V star, as S Mon is classified (Pagani 1973). We then conclude that these estimates corroborate that the ionization of the Cone is produced by S Mon. Similar conclusions have been reached before by Schwartz et al. (1985) and Schmidt (1974).

There are two relatively bright (about 20 mJy at 6 cm; Girart et al. 2002) sources about 8′ to the NW of the Cone Nebula. These sources are known to have non-thermal spectra (Schwartz et al. 1985) and most probably are background galaxies. This
Figure 4. VLA images showing the polarization of the west side of the jet for 2006 (left) and 1995 (right). The parameters are as in Figure 3.

Figure 5. This figure shows the Cone Nebula in grayscale taken from the red image of the DSS archives. The grayscale bar at the top indicates the intensity of the optical image in arbitrary units. The contours come from 6 cm VLA-D archive data. The bright, compact double-source to the NE of the head is the non-thermal radio jet studied in this paper. The bright, compact double-source to the NE of the head is the non-thermal radio jet studied in this paper. The diffuse radio emission associated with the head and “shoulder” of the Cone Nebula is most probably free–free emission from gas photoionized by the massive O-type binary S Mon, located about 30′ to the north of the nebula. The contours are $-4, 4, 6, 8, 10, 20, 40, 60, 80,$ and 100 times 112.7 $\mu$Jy, the rms noise of the radio image. The half-power contour of the synthesized beam of the radio image (18′.5 $\times$ 15′.0; $PA = 0^\circ$) is shown in the bottom left corner.

result suggests that the non-thermal jet may be associated with one of the galaxies of an extragalactic background cluster. Unfortunately, given the large obscuration of the region, there are no optical counterparts to any of these sources to further test the possible presence of a cluster.

4. SUMMARY

We searched for proper motions and flux variability in the NGC 2264 non-thermal radio jet. We found no proper motions larger (at a 3$\sigma$ upper limit) than 1.6 mas yr$^{-1}$. This stringent upper limit appears to rule out a galactic location for the jet, either in the case of a thermal jet emanating from a young star or a relativistic microquasar. We found flux variations only in one knot of the jet, which we identify as the core of the source.

The high degree of linear polarization in the jet and its spatial structure are comparable with other cases of extragalactic jets. With this evidence, we believe that this object is an extragalactic jet seen in the line of sight toward the NGC 2264 star forming region, even when the a priori probability of such coincidence is very low.

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