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# ON THE NATURE OF THE NON-THERMAL RADIO SOURCE AT THE CENTER OF THE ORION STREAMERS

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RESUMEN

Presentamos un análisis de observaciones del VLA en el continuo a 20 y 6 cm hacia una fuente de radio no térmica en la región de las Serpentinas (*Streamers*) en Orión. Comparamos observaciones de archivo de 1991 con nuevas observaciones hechas por nosotros en 2008. Dicha fuente puede ser un objeto estelar joven o un objeto evolucionado, como un microcuasar, o incluso un jet de una radiogalaxia. Nuestro análisis muestra que no hay evidencia de cambio en la densidad de flujo, entre ambas épocas, arriba del 10%, y que la morfología permanece constante dentro del ruido. Tampoco hay indicio de movimientos propios mayores que 23 msa año$^{-1}$, a un nivel de $3\sigma$, que a la distancia de Orión implican un límite superior a la velocidad en el plano del cielo de $\sim$ 45 km s$^{-1}$. A 6 cm detectamos emisión polarizada linealmente con un nivel de $\sim$ 5%, mientras que a 20 cm no se detecta esta emisión por encima de $\sim$ 2%. Concluimos que esta fuente de radio no térmica es muy probablemente una radiogalaxia vista por mera casualidad en la línea de visión hacia el centro del sistema de las Serpentinas de Orión.

ABSTRACT

We present VLA continuum observations at 20 and 6 cm toward a non-thermal radio source located at the *Streamers* region in Orion. We compare 1991 archive observations with new ones taken by us in 2008. The radio source could be a young stellar source or an evolved object like a microquasar or even a jet from a radio galaxy. Our analysis shows that there is no evidence of changes in the flux densities between both epochs at a level higher than 10%. Also, we set an upper limit at a $3\sigma$ level of 23 mas year$^{-1}$ for the proper motions. At the distance of Orion this implies an upper limit to the velocity in the plane of the sky of 45 km s$^{-1}$. At 6 cm, we detect linearly polarized emission at a level of $\sim$ 5%, while at 20 cm we do not detect this emission above a level of $\sim$ 2%. We conclude that the non-thermal radio source most probably is a radio galaxy aligned by chance with the line of sight to the Streamers in Orion.

*Key Words:* ISM: individual (Orion Streamers, HH 222) — radiation mechanisms: non-thermal — radio continuum: ISM



## 1. INTRODUCTION

The system known as the Streamers in Orion is an elongated, arc-like optical structure in the L1641 cloud in Orion. It stretches in the sky for 5 arcmin in the NE-SW direction. The system has optical line emission (Cohen & Schwartz 1983) and is very close to the HH-34 system. There is a T Tauri star located at only 15 arcsec from the center of the system. On the basis of this association, the arc was suggested to be the result of an interaction from the wind of this star with the surrounding medium (Reipurth & Sandell 1985).

In 1990, Yusef-Zadeh et al. (1990) reported a non-thermal radio source detected with the VLA in that region. The source is linearly polarized at a level of 5% in the 6 cm emission and is located at the very center of the Streamers with its main axis approximately aligned with the axis of the system. These

TABLE 1

PARAMETERS OF THE OBSERVATIONS

| | Flux Density (Jy) 0541-056 | | Image rms noise ($\mu$Jy) | |
|---|---|---|---|---|
| Epoch | 20 cm | 6 cm | 20 cm | 6 cm |
| 1991.64 | $1.20 \pm 0.02$ | $1.24 \pm 0.03$ | 80.6 | 26.7 |
| 2008.79 | $1.20 \pm 0.10$ | $1.27 \pm 0.07$ | 61.5 | 26.3 |

authors also found a 2-micron source at the position of the radio source and several low-mass young stars in the surroundings of it. They concluded that the non-thermal radio source could be a newly born star.

A different interpretation of this association was given by Castets, Reipurth, & Loinard (2004), who proposed that this radio source could be the result of a T Tauri star undergoing an energetic event or to emission from an X-ray binary system. However, using millimeter studies of the CO, $^{13}$CO, C$^{18}$O and CS molecules emission around a region centered in the Streamers, Castets et al. (2004) found no evidence to link the radio source with any molecular outflow. Since the probability of finding this radio source to be just a fortuitous alignment is only $7.5 \times 10^{-5}$ (Castets et al. 2004), the most probable interpretation was in terms of this source being an evolved galactic object.

In these cases, there always exists the possibility of a fortuitous alignment. We decided to test this hypothesis using new VLA observations. Since the source is at $\sim -20°$ of Galactic latitude, relatively far from the galactic plane, we found that the existing HI absorption observations were not useful to test the distance to the source, given the lack of line-of-sight gas in that direction. Thus our new observations were planned to study any possible flux variability, morphology changes and proper motions. To acomplish this, we used 1991 archive observations plus new observations performed by us.

At the distance of the Streamers, proper motions over two decades would be of the order of 2 arcsec for a velocity of 200 km s$^{-1}$, which is expected for Herbig-Haro objects. Typically, also flux variability would be present in these cases (Rodríguez et al. 2000). For the extended radio lobes of an extragalactic source we would not see any proper motion, perhaps only flux changes between both epochs, arising in a possible compact core located between the lobes.

We present this work as a part of a series of studies of non-thermal radio sources apparently associated with galactic star forming regions or nebulae. We have previously shown that an association on the plane of the sky is not always a physical association (Trejo & Rodríguez 2006, 2008, 2010).

## 2. OBSERVATIONS

We made our new observations with the VLA, an NRAO[1] telescope. The observations were planned for the A configuration and taken on October 16, 2008 (epoch 2008.79) under project AT 368. We matched the parameters of our observations to those of the August 20, 1991 (epoch 1991.64) archive observations made under project AY 037. Thus, the pointing center, the frequency, and the calibrators are the same. The rms noise is roughly the same in both data sets, as is the *uv* coverage, which allows a reliable comparison between both epochs.

A total of 26 antennas in the A configuration were present at the time of the observations, both in 1991 and 2008. The flux calibrator was 1331+305 at both epochs and for both frequencies. To calibrate the phase, the source 0541-056 was used, with bootstrapped flux densities at both epochs and wavelengths indicated in Table 1. At 20 cm, a total of 1.25 hours was spent on the source in 2008, and 1.96 hours in 1991. At 6 cm, the times were 1.15 hours for 2008 and of 2.00 hours for 1991.

Since the source is weak at 6 cm, we made the images setting the robust parameter of the task IMAGR to 0, which produces images with the best compromise between angular resolution and noise level. The 20 cm observations show a brighter source, and a scheme with uniform weighing (robust parameter set to $-5$) is used, since it allows the highest angular resolution possible. This is important to look for the existence of morphology changes and proper motions. The data at both frequencies were calibrated and imaged following the standard procedures listed in the AIPS Cookbook.

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

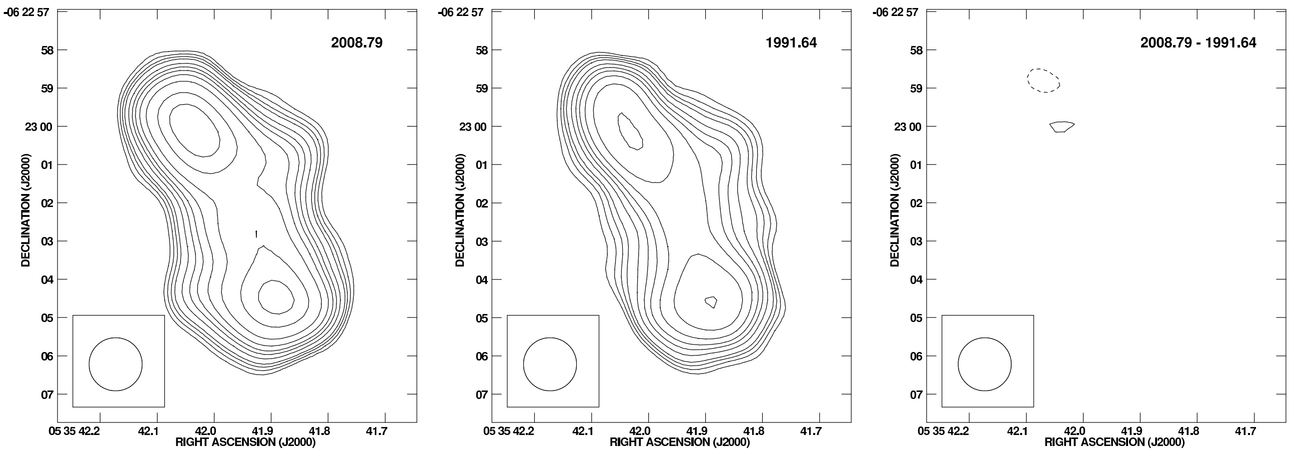


Fig. 1. 20 cm continuum images for the non-thermal source VLA J05354198–0623018. Left: 2008 image with an rms noise of 61.5 $\mu$Jy. Center: 1991 image with an rms noise of 80.6 $\mu$Jy. Right: Residual image 0.92 × 2008 - 1991, the rms noise is 95.7 $\mu$Jy. The levels for all images are −3, −4, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, and 40 × the individual rms noise. The full-width half maximum of the restoring beam is 1″.39 × 1″.39 and is shown in the bottom left corner.

## 3. RESULTS AND DISCUSSION

We shifted the position of the phase calibrator in 1991 to that of 2008 to remove a small offset, which is necessary because of the continuous refinement of the calibrator positions made by NRAO personnel. Also, in order to reliably compare both data sets we made images convolved with a circular beam of 1″.39 for the 20 cm data, and of 0″.47 for the 6 cm data.

### 3.1. *20 cm*

After performing the normal imaging for the 20 cm observations, we still detected a small offset, of the order of 0″.03 in declination and 0″.17 in right ascension, between the 2008 and 1991 images. To test if the offset seen in the data was a real position change of the source or an observational problem, we measured the positions of four sources located inside the primary beam of the telescope. All of them showed roughly the same small offset between both epochs. We then conclude that the offset is most likely an observational problem, perhaps produced by the fact that the 1991 observations were made near solar maximum, which can affect the long wavelength observations and produce positional errors such as those observed (Kaplan et al. 1982). A phase cross-calibration was performed to the data to minimize the diferences in phase between both observations. We could then compare reliably the images and search for morphology changes and flux variations, if any. To subtract the images we used a scheme to minimize the rms noise of the difference image (Franco-Hernández & Rodríguez 2004). This is done by selecting the appropriate weight to one data set while making the subtraction. In this case we made the subtraction as 2008 image – $1.09 \times 1991$ image. This allows to correct any calibration error in the flux scale. We present in Figure 1 the maps for the 20 cm emission at both epochs, and also the difference image resulting from the subtraction, made as we just noted. The morphology is that of a well-defined double component source. We refer to the source as VLA J05354198–0623018, where the coordinates are those of the centroid of the source. The total flux density obtained is about 20 mJy. The right panel of Figure 1 shows there are no residuals above a $3\sigma$ level of 0.3 mJy. The average total flux density of the source from both epochs is $17.9 \pm 0.6$ mJy.

We also looked for proper motions by measuring the positions of the two lobes of the source at the two epochs. The analysis showed that there were no proper motions larger than 10 mas year$^{-1}$ at a $3\sigma$ level. Taking the distance to Orion to be 414 pc (Menten et al. 2007), that limit implies velocities below 20 km s$^{-1}$. However, since the data at both epochs were aligned with the phase cross-calibration, we will use the more reliable upper limits obtained at 6 cm (see below).

To look for polarized emission at this frequency, several tests with different weighting schemes were applied to the data. We did not find any polarization in the data at a level larger than 2%.

### 3.2. *6 cm*

At 6 cm, VLA J05354198–0623018 is weaker which makes a cross-calibration harder to perform.

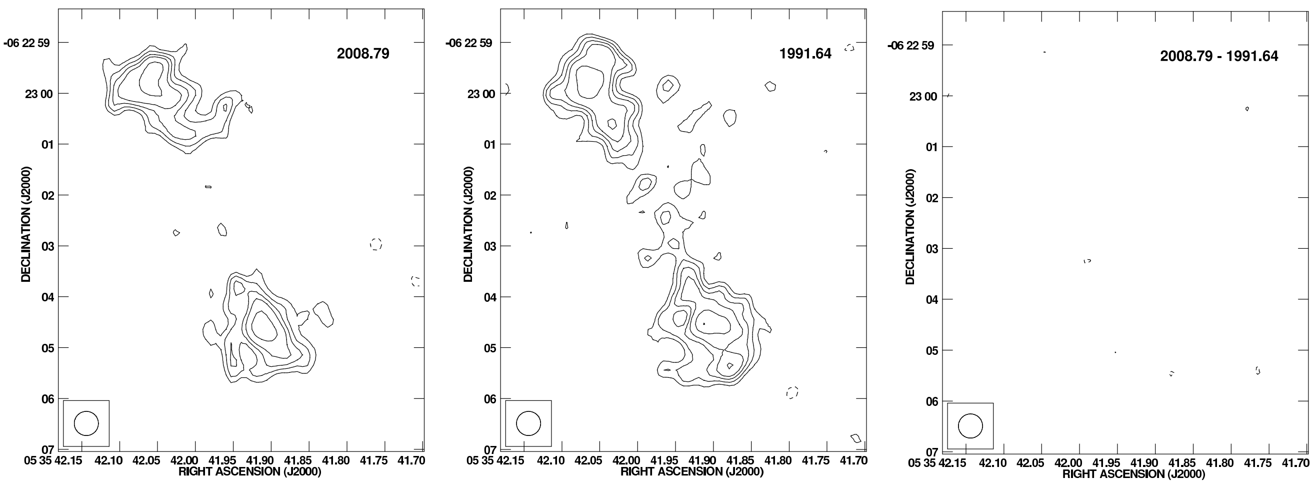


Fig. 2. 6 cm continuum images for the non-thermal source VLA J05354198–0623018. Left: 2008 image, the rms noise is 26.3 $\mu$Jy. Center: 1991 image with an rms noise of 26.7 $\mu$Jy. Right: Residual image 2008 – 1991, the rms noise is 36.8 $\mu$Jy. The levels for all the images are $-3$, $-4$, 3, 4, 5, 6, 8, 10, 12, 15, 20, 30, and 40 $\times$ the individual rms noise. The full-width half maximum of the restoring beam is $0\farcs47 \times 0\farcs47$ and is shown in the bottom left corner.

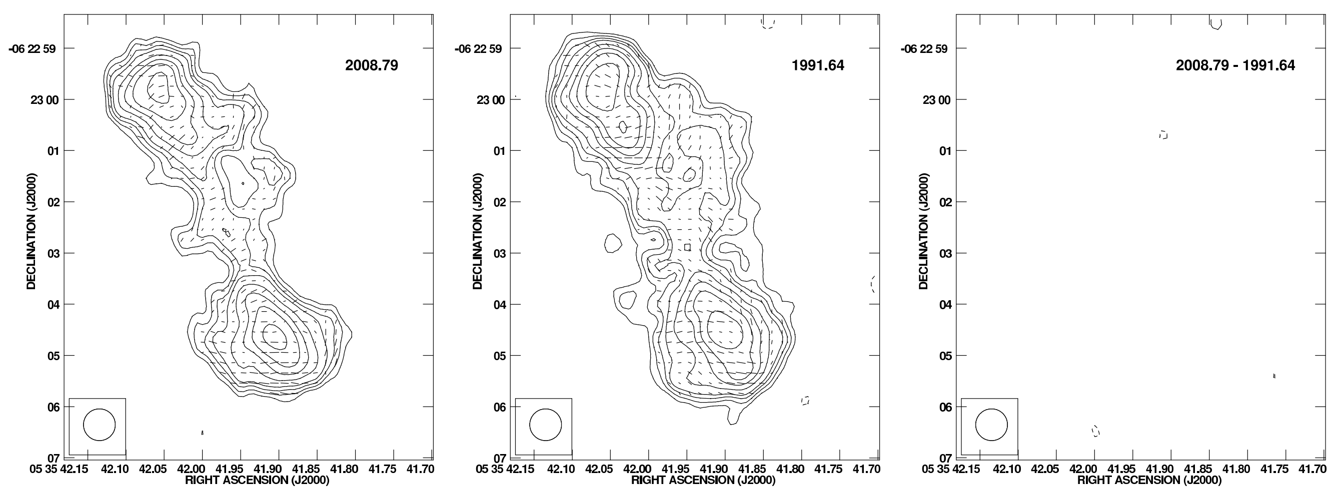


Fig. 3. 6 cm continuum images made with natural weighing showing polarized emission as vectors. A 0.5 arcsec line represents a polarization of 5%. Left: 2008 image with rms noise of 25.54 $\mu$Jy. Center: 1991 image with rms noise of 23.30 $\mu$Jy. Right: 2008 - 1991 image with rms noise of 32.33 $\mu$Jy. Levels are as in previous figures. The full-width half maximum of the restoring beam is $0\farcs62 \times 0\farcs62$ and shown in the bottom left corner.

In addition, the data sets did not present the same small instrumental misalignment as did the 20 cm observations. Then, there was no need for a phase cross-calibration, apart from the shifting of the 1991 data for the refinement of the position of the phase calibrator. Neither was a scale correction in flux density needed. In Figure 2 we present both images for 2008 and 1991, as well as the subtracted image. At this resolution, the images clearly split into two main components. The average total flux density from both epochs is $7.7 \pm 0.5$ mJy. As can be seen in the right panel of Figure 2, the residual image shows no evidence of emission at all, at least not above a $3\sigma$ level of 0.1 mJy. The morphology remains essentially the same.

The spectral index from the 20 and 6 cm measurements is $\alpha = -0.67 \pm 0.06 (S_\nu \propto \nu^\alpha)$. This value is characteristic of extragalactic radio jets (Bridle & Perley 1984).

By measuring the peaks of the two main lobes of VLA J05354198–0623018 at the two epochs, we set an upper limit for proper motions of $3\sigma$ of

23 mas year$^{-1}$, equivalent to $\sim$ 45 km s$^{-1}$ at the distance of Orion.

Contrary to the case of the 20 cm emission, we detected linearly polarized emission at 6 cm. In Figure 3 we show maps of the two epochs and also the residual image. The maps were made with natural weighting in order to have the lowest rms noise possible. The electrical vectors are shown with their length proportional to the degree of polarization. Yusef-Zadeh et al. (1990) reported a level of polarization of 5%, and we confirmed this value both with the 1991 archive data and with our new 2008 observations. The position angles for the electrical vectors in Figure 3 are consistent with those reported in their study at a lower angular resolution. The polarization level found in this source is within the range of 5% to 40% observed in most extragalactic radio jets (Bridle & Perley 1984).

The Faraday rotation measure in the direction of HH 222 is $\sim$ 20 radians per square meter (Johnston-Hollitt, Hollitt, & Ekers 2004). This implies rotations of order 0.07 radians ($\sim 4°$) and 0.8 radians ($\sim 46°$) at 6 and 20 cm, respectively. This difference in the expected rotations suggests that the non-detection of polarization at 20 cm could be due to Faraday depolarization.

Since the upper limit to the velocity implied by the proper motions at 6 cm is of the order of $\leq 45$ km s$^{-1}$, we do not favor a galactic location for the non-thermal source. As we noted, HH objects have velocities of the order of 200 km s$^{-1}$. Microquasars have ejecta that move at relativistic speeds and we can rule them out. Also, the absence of significant residual emission and the fact that no essential morphological changes at both frequencies were observed support an extragalactic location. We propose this source to be a radio galaxy. The double lobe morphology seen at both frequencies is typical of radio galaxies.

## 4. CONCLUSIONS

We present 20 and 6 cm observations of the non-thermal source VLA J05354198–0623018 at the very center of the Streamers system in Orion. The probability of this source to be an alignment by chance is very low, as we noted. However, the upper limit to the velocity implied by the absence of detectable proper motions and the lack of significant morphology variation weigh against a physical association with the Orion region. The polarization is consistent with that present in radio galaxies. We conclude that the radio source is most probably an extragalactic one, apparently a radio galaxy in the line of sight to the Streamers.

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