INVESTIGATING PARTICLE ACCELERATION IN PROTOSTELLAR JETS: THE TRIPLE RADIO CONTINUUM SOURCE IN SERPENS

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ABSTRACT

While most protostellar jets present free–free emission at radio wavelengths, synchrotron emission has also been proposed to be present in a handful of these objects. The presence of nonthermal emission has been inferred by negative spectral indices at centimeter wavelengths. In one case (the HH 80-81 jet arising from a massive protostar), its synchrotron nature was confirmed by the detection of linearly polarized radio emission. One of the main consequences of these results is that synchrotron emission implies the presence of relativistic particles among the nonrelativistic material of these jets. Therefore, an acceleration mechanism should be taking place. The most probable scenario is that particles are accelerated when the jets strongly impact against the dense envelope surrounding the protostar. Here we present an analysis of radio observations obtained with the Very Large Array of the triple radio source in the Serpens star-forming region. This object is known to be a radio jet arising from an intermediate-mass protostar. It is also one of the first protostellar jets where the presence of nonthermal emission was proposed. We analyze the dynamics of the jet and the nature of the emission and discuss these issues in the context of the physical parameters of the jet and the particle acceleration phenomenon.

Key words: acceleration of particles – ISM: jets and outflows – ISM: kinematics and dynamics – ISM: magnetic fields

1. INTRODUCTION

Jets from young stellar objects (YSOs) have long been studied at radio wavelengths (e.g., Rodríguez 1995, 1996; Anglada 1996; Carrasco-González et al. 2012; Anglada et al. 2015). Free–free interactions between thermal electrons and protons in these partially ionized jets produce detectable free–free continuum emission at centimeter wavelengths with a characteristic positive spectral index (α, defined as Sν ∝ ν−α). High angular resolution observations at radio wavelengths allow the jet material to be traced up to a few tens of astronomical units (AU) from the protostar. In this way, the base of the large parsec-scale jets (which cannot be observed at optical or IR wavelengths owing to the large extinction near the protostar) can be studied. These radio sources are called thermal radio jets, in contrast to the radio jets usually observed emanating from active galactic nuclei (AGNs), whose main emission mechanisms at radio wavelengths are of nonthermal nature (optically thin synchrotron emission), and show very different characteristics: negative spectral indices at centimeter wavelengths and linear polarization.

In recent decades, radio emission with negative spectral indices at centimeter wavelengths has also been detected in several YSO jets, such as the triple radio source in Serpens (Rodriguez et al. 1989), HH 80-81 (Martí et al. 1993), IRAS 16547−4247 (Garay et al. 1996; Rodríguez et al. 2005), W3(H2O) (Wilner et al. 1999), and L778-VLA 6 (Girart et al. 2002) and DG Tau (Ainsworth et al. 2014). It is usually proposed that these negative spectral indices are related to the presence of synchrotron emission from these objects. The synchrotron nature in a YSO jet was confirmed in the case of HH 80-81, where polarized emission was detected through sensitive radio observations at 6 cm (Carrasco-González et al. 2010). Synchrotron emission implies the presence of relativistic particles. However, jets from YSOs are launched at relatively low velocities (in comparison with the jet velocities in AGNs), of the order of only several hundreds of kilometers per second. Therefore, an acceleration mechanism should be taking place in these objects in order to attain a population of relativistic particles that could produce detectable synchrotron emission. One possibility is that the acceleration of particles takes place in strong shocks where the jet impacts against the ambient medium. In this situation, particles could gain energy by diffusing back and forth across a shock front (e.g., Drury 1991). This process, known as diffusive shock acceleration (DSA), allows that particles originally moving at a few hundreds of kilometers per second can reach relativistic velocities. The DSA mechanism is known to work in AGN jets (e.g., Blandford et al. 1982), supernova remnants (e.g., Castro & Slane 2010), nova ejecta (e.g., Kantharia et al. 2014), and colliding wind binaries (e.g., De Becker 2007), where shocks with velocities of at least several thousand kilometers per second are present. In this sense, protostellar jets could be a new extreme testing ground for DSA theory.

The Serpens star-forming region is located at a distance of ~415 pc (Dzib et al. 2010) and contains one of the first radio jets proposed to be a synchrotron emitter. This source, called the triple radio source in Serpens, has a morphology consisting of a central thermal radio continuum source (positive spectral index) and two outer nonthermal lobes (negative spectral...
indices). Moreover, the outer knots show proper motions of the order of a few hundred kilometers per second, suggesting that they are tracing out the motion of the jet against the ambient medium (Rodríguez et al. 1989; Curiel et al. 1993). In this article, we present an analysis of new and archive data at radio wavelengths of the triple radio source in Serpens and discuss the results in the context of particle acceleration and synchrotron emission production.

2. OBSERVATIONS

Observations of the triple radio source in Serpens were made with the Karl G. Jansky Very Large Array (VLA) of the National Radio Astronomy Observatory (NRAO).\(^8\) We observed the continuum emission in the S, C, and X bands in B configuration during 2012 June 12 and 16 (project code: 12A-240). For each band, we observed a total continuum bandwidth of 2 GHz covering the frequency ranges 2–4 GHz, 4.5–6.5 GHz, and 8–10 GHz in S, C, and X bands, respectively. Each band is divided into 1024 channels of 2 MHz. Bandpass and flux calibration were made by observing 3C 286. Complex gain calibration was achieved by observation of 1824+1044 every 10 minutes. We also performed polarization calibration by using 3C 286 as the polarization angle calibrator and the unpolarized source 2355+4950 as the leakage calibrator. The phase center of our observations was Ω (J2000) = 18\(^{h}\)29\(^{m}\)49.8\(^{s}\), δ (J2000) = +01\(^{d}\)15\(^{m}\)20\(^{s}\).

We additionally analyzed VLA archive data taken at C band in the A configuration at eight epochs spanning 18 yr, from 1993 to 2011. In these observations, flux calibration was achieved by observing 3C 286, while phase calibration was performed by using 1751+096. Calibration of the data was undertaken with the data reduction package Common Astronomy Software Applications (CASA\(^9\); version 4.1.0) following standard VLA procedures. Cleaned images were made using the task clean of CASA. For the 2 GHz bandwidth images we used multifrequency synthesis (parameter nterms = 2) and multiscale cleaning (Rau & Cornwell 2011). For these data, we made images selecting different bandwidths: 512 MHz, 2 GHz, and a single image using all three bands (S, C, and X). We used different values of the parameter robust of clean, ranging from −2 (uniform weighting) to +2 (natural weighting). For the analysis of the multipeoch archive data, we made images for each epoch by using parameter nterms = 1 and also different values of the robust parameter. In order to better compare the images from the different epochs, we convolved all the images to the same beam size.

A summary of the observations and image parameters is shown in Tables 1 and 2, respectively.

3. RESULTS

In Figure 1 we show the continuum image (contours) obtained by using all the B configuration data in S, C, and X bands, as well as the spectral index map (color scale) obtained from the multifrequency synthesis cleaning. In this figure, the jet-like morphology of the Serpens triple source is clearly seen. We identify four compact components: a central elongated source (C) and three outer knots (NW, NW_C, and SE). The three components C, NW_C, and NW are connected by extended emission, whereas no similar extended emission is detected connecting the central source to the SE component. The SE knot appears to be split into two different components, labeled as SE_N and SE_S, clearly seen in the higher angular resolution images (see below). In the following we discuss the characteristics of the radio jet.

3.1. Spectral Indices and Spectral Energy Distributions

In order to study the nature of the radio emission in the triple source in Serpens, we obtained a spectral index map (Figure 1) and the spectral energy distribution (SED) for each of the compact components in the jet (Figure 2). Both the spectral index map and the SEDs show a difference between the nature of the emission of the central component, the lobes, and the extended emission. The central source shows a clear positive spectral index (∼0.3), suggesting partially optically thick free–free emission and in good agreement with those of thermal radio jets (e.g., Anglada et al. 2015; Carrasco-González...
Notes.  
\(^a\) Combined data from May 09/30, June 01.  
\(^b\) Combined data from June 12/16.

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**Table 2**

Parameters of the Images

| Observation Date | Spectral Band | Configuration | Bandwidth (GHz) | Weighting | Synthesized Beam |
|------------------|---------------|---------------|-----------------|-----------|------------------|
| 1993 Jan 09      | C             | A             | 0.1             | Robust = 0 | 0.07' 42        |
| 1994 Mar 21      | C             | A             | 0.1             | Robust = 0 | 0.07' 42        |
| 1995 Jul 13      | C             | A             | 0.1             | Robust = 0 | 0.07' 42        |
| 1998\(^a\)       | C             | A             | 0.1             | Robust = 0 | 0.07' 42        |
| 2000 Oct 27      | C             | A             | 0.1             | Robust = 0 | 0.07' 42        |
| 2011 Jun 26      | C             | A             | 0.1             | Natural   | 0.07' 42        |
| 2012\(^b\)       | S             | B             | 2.0             | Uniform   | 2.0' 60         |
| 2012\(^b\)       | C             | B             | 2.0             | Uniform   | 2.0' 60         |
| 2012\(^b\)       | X             | B             | 2.0             | Uniform   | 2.0' 60         |
| 2012\(^b\)       | C             | B             | 2.0             | Natural   | 1.0' 40         |
| 2012\(^b\)       | X             | B             | 2.0             | Natural   | 1.0' 40         |
| 2012\(^b\)       | S+C+X         | B             | 6.0             | Robust = 0 | 1.0' 07 × 0.0' 30 PA = −58° |

Figure 1. Superposition of a radio continuum image made by combining data from S, C, and X bands of epoch 2012 (contours) over the spectral index image obtained from multifrequency synthesis cleaning (color scale). Contours are 4, 8, 16, 31, 64, and 128 times the rms of the continuum image, 6 \(\mu\)Jy beam\(^{-1}\). The synthesized beam size is 1.0' 07 × 0.0' 30, with a PA of −58°. The pixels shown in the spectral index image are those with an error in the spectral index of less than 0.1. We labeled the four components discussed in the paper (central source C and the outer knots SE\(_N\), SE\(_S\), NW, and NW\(_C\)).

- In contrast, the rest of the emission shows flat (\(\alpha \sim 0\)) or negative spectral indices, which suggests optically thin free–free emission and nonthermal emission, respectively.
- The spectral index of NW is \(-0.35 \pm 0.02\) and implies a nonthermal origin of the emission. The SED of the SE knot is more difficult to interpret. We know from the higher angular resolution images that this knot is composed of two radio knots (SE\(_N\) and SE\(_S\), separated by \(\sim 1''2\)). However, in the lower-frequency images, the angular resolution (\(\sim 2''6\)) is not high enough to separate the emission of these two components. The SED of this source obtained with low angular resolution appears very flat (see Figure 2, bottom left panel). However, if we consider the flux densities obtained in the higher angular resolution images (C and X bands, uniform weighting; beam size = 1.0' 4), we obtain a negative spectral index (\(-0.36 \pm 0.03\)) for the SE\(_N\) component. We then assume that the SED obtained from the low angular resolution images of SE can be decomposed in a nonthermal component (corresponding to SE\(_N\)) plus a thermal component (most probably arising from SE\(_S\)) (Figure 2). For component NW\(_C\) we also obtain a flat spectrum (Figure 2). However, from the spectral index image of Figure 1, which has higher angular resolution than the images used to construct the SED, we see that, at the position of the peak of NW\(_C\), we obtain a negative spectral index (approximately −0.3). This image suggests that the contribution from optically thin free–free emission arises from the extended emission that surrounds component NW\(_C\) and could not be separated in the low angular resolution images, from which the SED shown in Figure 2 has been determined. We therefore conclude that the NW\(_C\) component also has a nonthermal nature.

### 3.2. Polarization

Motivated by the detection of linearly polarized emission from the HH 80-81 jet (Carrasco-González et al. 2010), we carried out a polarization study with our new S, C, and X VLA data. These are the most sensitive data obtained so far in the Serpens region that allow polarization calibration. However, we did not detect linearly polarized emission from regions with negative spectral indices in the Serpens triple radio source (none of the 2 GHz images we made). In Table 3, we give upper limits for the polarization degree in the different nonthermal radio knots, implying that if linearly polarized emission is present, its polarization degree should be less than 10%.

There are two possibilities for this low polarization degree.

First, an important difference between HH 80-81 (with polarization degrees \(\sim 10\%–30\%\)) and the triple source in Serpens is that synchrotron emission from the former seems to be detected in a large portion of the radio jet, from 0.1 to 0.5 pc from the protostar (see Carrasco-González et al. 2010, 2013). It is then likely that most of the polarized emission is arising from a very collimated jet, where the magnetic field is expected to be well ordered. Indeed, the magnetic field lines in HH 80-81 seem to be parallel to the
direction of the jet (Carrasco-González et al. 2010). A well-ordered magnetic field would result in a relatively high polarization degree. In contrast, in Serpens, synchrotron emission seems to be detected mainly in the shocks against the ambient medium, where it is likely that the jet material is more turbulent. This could yield a magnetic field very disordered in these shocks and could result in a very low polarization degree. A second possibility is that the electron density in these shocks is high enough to result in a strong Faraday rotation of the polarization angle, resulting in a very low polarization degree when observed in a wide band. If this

| Knot | S Band (%) | C Band (%) | X Band (%) |
|------|------------|------------|------------|
| SE   | <6         | <5         | <7         |
| NW_C | <6         | <9         | <12        |
| NW   | <5         | <4         | <6         |

Note. Upper limits are obtained with the peak intensity of the radio knots and the rms of the maps. A 4σ upper limit was considered.
is the case, imaging with a smaller bandwidth (as was the case in the HH 80-81 observation of Carrasco-González et al. 2010) would allow us to detect higher polarization degrees. However, our observations of the triple radio source in Serpens were very short in time, and the high sensitivity comes from the fact that we are using wide bandwidths. Imaging of smaller frequency ranges does not allow us to obtain high-sensitivity images to explore this possibility. Observations with a much larger observation time should be necessary in order to investigate whether a strong Faraday rotation is present.

3.3. Proper Motions

We studied the kinematics of the different knots in the Serpens radio jet by analyzing the multiepoch high angular resolution archive data at 6 GHz (see Table 2 for multiepoch image parameters). We aligned the images obtained at different epochs by assuming that the central source has the same position in each of the observed epochs. In Figure 3 we show, in three columns, multiepoch images for the observed knots. The images are all shown with the same intensity scale to compare the fluxes at different epochs. We see that all knots are moving away from the central source. Measuring their displacements in each epoch and assuming a distance of 415 pc to the Serpens molecular cloud, we estimated the tangential (i.e., in the plane of the sky) velocities of the knots (Figure 4 and Table 4). We found that the NW and SE_S tangential velocities are similar (∼200 km s⁻¹), while the SE_N is moving faster (∼300 km s⁻¹). The velocities of these three knots seem to be constant during the analyzed epochs. On the other hand, we observe an interesting behavior in the NW_C knot: it moves away from the protostar with a very high velocity of ∼500 km s⁻¹ between 1993 and 1998, and after several years it dramatically decelerates to a velocity of only ∼40 km s⁻¹. Furthermore, the flux density of NW_C also varies with time, increasing when it moves fast, and decreasing when the velocity is low (see Figure 5). Recent observations at 7 mm performed by Choi (2009) detected a dusty filament-like structure that, in projection, seems to pass across the jet at the position where NW_C decelerates (see Figure 6). Therefore, we speculate that the NW_C decelerates after interacting with this dusty filament. In this case, an increase would be expected in the plasma density and therefore in the flux density.

In Figure 7 we show the positions of the knots relative to the central source for the six epochs between 1993 and 2011, as well as least-squares fits to the trajectories. The position angles (PAs) are derived for the motion of each component. Components NW, NW_C, and SE_S seem to be moving with similar PAs in the range 132°–136°. In contrast, component SE_N seems to move in a different direction with a PA of 126°. We also note that the central source appears elongated in all epochs with a PA of 119° ± 1°, which is closer to the value obtained for the motion of SE_N.

We also estimated the kinematic ages of the different knots, i.e., the time needed for them to move from the central source to their present position. We assume that SE_N, SE_S, and NW moved with constant velocity since they emerged from the central source. For NW_C, we adopt a constant velocity equal to the value measured before it decelerates in 1998. We found similar kinematic ages of ∼80 yr for NW and SE_S, which suggests that they both arose at the same time in ∼1930. This is also consistent with these two knots showing similar velocities (∼200 km s⁻¹) and a similar direction of their movement (PA ≈ 130°). For SE_N, we found a kinematic age of ∼60 yr, suggesting that it arose from the central source later, around ∼1950. The PA of this knot (126°) is different from that of the SE_S and NW knots, which suggests that the jet suffered a change in its PA of ∼10° in ∼20 yr. The youngest knot is NW_C, which we estimate was ejected from the central source around ∼1980. This knot moves in a direction with a PA similar to that of the earlier ejected knots SE_S and NW. This suggests that the jet again changed its direction between 1950 and 1980, to an orientation similar to that of 1930. Finally, the central source is currently elongated approximately in the direction of the SE_N knot. This behavior is consistent with precession of the jet and an episodic ejection phenomenon every 20–30 yr. If the periodicity of these strong ejecta were confirmed, it would suggest the presence of a close companion orbiting around the driving source of the radio jet. Precession of the jet axis could be driven by tidal interactions between the disk from which the jet originates and a companion star in a non-coplanar orbit (Masciadri & Raga 2002; Anglada et al. 2007).

Several authors have proposed that the central source of the triple radio source in Serpens is actually a binary system of YSOs (e.g., Eiroa & Casali 1989; Hodapp 1999; Eiroa et al. 2005; Choi 2009; Dionatos et al. 2010). Indeed, Dionatos et al. (2014) found evidence of the existence of a binary companion, lying at 1.5° to the NW, which corresponds to a separation in the plane of the sky of ∼622 AU. We investigated whether this companion could be responsible for the observed jet precession in our VLA data through tidal interactions. Following the equations presented in Anglada et al. (2007), it is possible to infer the separation of the binary system from the precession of the jet. Hence, assuming a period of 20–30 yr and β = 10° (the angle between the central flow axis and the line of maximum deviation of the flow from this axis), the separation between the components of a binary system responsible for the precession should be ∼3 AU. Therefore, if the observed ejections have a binary system origin, the companion orbiting around the driving source of the radio jet should be much closer than the companion detected by Dionatos et al. (2014). This would require very high angular resolution observations to be confirmed. Furthermore, if the source reported by Dionatos were responsible for the precession, it should be located roughly perpendicular to the jet axis.

4. DISCUSSION: ON THE PARTICLE ACCELERATION AND SYNCHROTRON EMISSION

Protostellar jets usually show a simple morphology at radio frequencies, consisting of an elongated source with a positive spectral index interpreted as free–free emission from ionized material tracing out the base of the large-scale jet (Anglada et al. 1998). The triple source in Serpens also shows this central free–free radio source. However, as in the case of other protostellar radio jets, such as HH 80-81, it also shows nonthermal radio knots located at larger distances from the central protostar. The most likely scenario to explain the presence of these nonthermal radio knots is that they are tracing strong shocks against the ambient medium where it is possible to accelerate particles that emit synchrotron radiation. However, this phenomenon only seems to be possible in some protostellar jets. In the following, we discuss the physical properties of the triple radio source in Serpens and their relationship to the particle acceleration phenomenon.
The intriguing aspect of particle acceleration in protostellar jets is to understand how these relatively slow jets are able to accelerate particles up to relativistic velocities. One possibility is that these nonthermal protostellar jets are particularly fast. Indeed, in the case of HH 80-81, proper motions of internal shocks suggest jet velocities of $\sim 1000$ km s$^{-1}$ (Martí et al. 1995). These velocities are considerably large compared with typical velocities in protostellar jets, of the order of a few hundreds of kilometers per second (e.g., Rodríguez et al. 2000; Estalella et al. 2012). In the case of Serpens, there are no observations with an angular resolution high enough to measure the velocity of the jet material as it emerges from the protostar. However, we have measured proper motions of $\sim 200$–300 km s$^{-1}$ of nonthermal ($\alpha \sim -0.35$) radio knots located at $z \approx 9'' \approx 0.02$ pc from the central source. We interpret these knots as synchrotron emission produced where the jet impacts against the ambient medium (see Figure 8). Therefore, if the molecular cloud is denser than the jet at the position of the shock, the jet velocity should be larger than the velocities observed in the

![Image of VLA C-band, A configuration intensity images of the components of the Serpens radio jet in different epochs. All images are convolved to the same circular beam size, 0$''$47. The comparison of the different images reveals proper motions of the outer knots (SE_N, SE_S, NW_C, and NW). The separations between images of epochs from 1993 to 2000 are proportional to the separations in time. Dashed red lines join the positions of the knots in different epochs up to 2000. White marks in the 2011 image correspond to the positions of each knot at epoch 2000.](image)
synchrotron radio knots since the material of the jet should slow down in the shock.

Synchrotron emission at 6 cm is produced by relativistic electrons with Lorentz factors \( \gamma_0 \sim 60(B/\text{mG})^{-1.5} \) in a magnetic field \( B \). These particles can be accelerated in the bow shock with the ambient medium or in the jet reverse shock (Mach disk). The acceleration mechanism depends on the nature of the shocks, radiative or adiabatic (i.e., nonradiative). A way to discern whether the shocks are radiative or adiabatic is by comparing the thermal cooling distance \( d_{\text{cool}} \) with the radius of the jet at the position of the shock, \( r_{\text{jet}} \) (Blondin

| Source | \( \mu \) (mas yr\(^{-1}\)) | \( v \) (km s\(^{-1}\)) | PA (°) |
|--------|-----------------|-----------------|--------|
| SE_{N} | 152 ± 1         | 299 ± 2         | 126 ± 1|
| SE_{S} | 113 ± 1         | 222 ± 2         | 132 ± 1|
| NW_{C}^a | 280 ± 10       | 543 ± 26        | 133 ± 1|
| NW_{C}^b | 21 ± 2          | 42 ± 3          | 133 ± 1|
| NW     | 104 ± 1         | 205 ± 2         | 136 ± 1|

Notes.

^a Before 1997.

^b After 1997.
The cooling distance can be estimated as

\[ d_{\text{cool}} = 2 \times 10^{13} \left( \frac{n}{100 \text{ cm}^{-3}} \right)^{-1} \times \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^{-4.51} \text{ cm; } v_s < 80 \text{ km s}^{-1} \] (1)

\[ d_{\text{cool}} = 1.7 \times 10^{14} \left( \frac{n}{100 \text{ cm}^{-3}} \right)^{-1} \times \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^{4.73} \text{ cm; } 80 < v_s < 400 \text{ km s}^{-1} \] (2)

\[ d_{\text{cool}} = 2.24 \times 10^{14} \left( \frac{n}{100 \text{ cm}^{-3}} \right)^{-1} \times \left( \frac{v_s}{100 \text{ km s}^{-1}} \right)^{4.5} \text{ cm; } v_s > 400 \text{ km s}^{-1}, \] (3)

where \( n \) is the density of the medium where the shock is propagating and \( v_s \) is the velocity of the shock. In the case of Serpens, we can estimate \( r_{\text{jet}} \) by taking half of the beam size of the highest angular resolution observations presented here, since the shocks appear unresolved, i.e., \( r_{\text{jet}} \approx 0''235 \approx 1.5 \times 10^{15} \text{ cm} \). In what follows we discuss the conditions required to accelerate electrons up to \( \gamma_0 \) in the bow shock and in the Mach disk.

4.1. Synchrotron Emission from the Shocked Molecular Cloud

Assuming that the jet is in the plane of the sky, the bow shock velocities are \( v_{\text{bs}} \approx 200-300 \text{ km s}^{-1} \), as obtained from our proper-motion analysis. Therefore, we calculate the cooling distance with Equation (2) assuming that the density \( n \) is the ambient density \( \left(n = n_{\text{amb}}\right)\) and the shock velocity is the measured bow-shock velocity \( \left(v_s = v_{\text{bs}}\right)\). The density of the molecular cloud, obtained through ammonia emission, is estimated as \( n_{\text{amb}} \approx 4 \times 10^4 \text{ cm}^{-3} \) (Curiel et al. 1996). Then, we find \( d_{\text{cool,bs}}/r_{\text{jet}} = 0.02 \), which implies that the shocks against the molecular cloud are radiative. In this situation, the flat spectral index detected in the radio knots can be explained as acceleration and compression of cosmic rays in the molecular cloud, as was suggested for old supernova remnants (i.e., in the radiative phase) emitting synchrotron radiation (Chevalier 1999). Another possibility is that electrons are accelerated through second-order Fermi acceleration (Ostrowski 1999).

4.2. Synchrotron Emission from the Shocked Jet

In order to study the conditions in the reverse shock, we need to know the jet parameters. The velocity of the reverse shock can be estimated as

\[ v_{\text{rs}} = v_{\text{jet}} - 3v_{\text{bs}}/4, \] (4)

while the jet velocity is given by (Raga et al. 1998)

\[ \frac{v_{\text{jet}}}{v_{\text{bs}}} = \frac{1 + \beta}{\beta}, \quad \beta = \sqrt{\frac{n_{\text{jet}}}{n_{\text{amb}}}}. \] (5)
that result in an adiabatic reverse shock
500 km s\(^{-1}\)

we see that, in order for the Mach disk to be a nonradiative shock, a mass-loss rate

Figure 9. We plot the ratio \(d_{\text{cool},i}/v_{\text{jet}}\) (grayscale) for different combinations of \(M\) and \(v_{\text{jet}}\). The solid line separates the jet conditions that result in adiabatic shock (i.e., \(d_{\text{cool},i} > r_{\text{jet}}\)) from those that result in radiative shocks. We also show two dashed lines corresponding to \(v_{\text{bs}} = 200\) and 300 km s\(^{-1}\). We can see that in order to be the Mach disk, an adiabatic shock, a mass-loss rate \(M \lesssim 5 \times 10^{-7} M_\odot\) yr\(^{-1}\), and \(v_{\text{jet}} \gtrsim 500\) km s\(^{-1}\) are needed.

For a pure hydrogen conical jet with opening angle \(\theta\) and a mass-loss rate \(M\), the jet density is given by (Reynolds 1986)

\[
\left( \frac{n_{\text{jet}}}{\text{cm}^{-3}} \right) = \frac{3.95 \times 10^7}{4\pi (1 - \cos \theta/2)} \left( \frac{M}{M_\odot \text{yr}^{-1}} \right) \times \left( \frac{v_{\text{jet}}}{\text{km s}^{-1}} \right)^{-1} \left( \frac{z}{\text{pc}} \right)^2.
\]

(6)

For the Serpens radio jet we estimate an opening angle of \(\theta \sim r_{\text{jet}}/z \sim 3^\circ\), with \(z\) being the distance from the central source to the shocks. The jet velocity, jet density, and mass-loss rate are unknown parameters. However, since all the jet parameters are related through the previous equations, we explored different possibilities. We assumed different combinations of \(10^{-7} \lesssim M \lesssim 10^{-5} M_\odot\) yr\(^{-1}\) and \(400 \lesssim v_{\text{jet}} \lesssim 1200\) km s\(^{-1}\). Then, given \(v_{\text{jet}}\) and \(M\), we calculate \(n_{\text{jet}}, v_{\text{bs}},\) and \(v_{\text{cs}}\) using Equations (4)–(6). The cooling distance is calculated with Equations (1)–(3), where the density \(n\) is the jet density \((n = n_{\text{jet}})\), and the shock velocity equals the reverse-shock velocity \((v_s = v_{\text{cs}})\). In this way, we can study whether a given pair of \(v_{\text{jet}}\) and \(M\) results in an adiabatic or radiative reverse shock.

The results of the above procedure are shown in Figure 9. In this figure, we show a line that separates the combinations of \(M\) and \(v_{\text{jet}}\) that result in an adiabatic reverse shock (i.e., \(d_{\text{cool},i} > r_{\text{jet}}\)) from those that result in radiative reverse shocks. We also show two lines corresponding to \(v_{\text{bs}} = 200\) and 300 km s\(^{-1}\), the observed velocities of the bow shocks. We can see that, in order for the Mach disk to be a nonradiative shock and the bow shocks to move with the observed velocities, the jet should have a mass-loss rate \(M \lesssim 5 \times 10^{-7} M_\odot\) yr\(^{-1}\) while the jet material should move at velocities \(v_{\text{jet}} \gtrsim 500\) km s\(^{-1}\). This suggests that a jet with a typical mass-loss rate for an intermediate-mass protostar is able to accelerate particles via the DSA mechanism if the velocity of the jet is high enough.

In such a case, electrons can be accelerated via DSA and injected in the shock downstream region following a power-law energy distribution \(\propto \gamma^{-p}\), with \(p = 2\). This population of nonthermal electrons produces synchrotron emission with spectral index \(\alpha = (1 - p)/2 = -0.5\). We note, however, that \(p = 2\) is also possible in oblique shocks given that the diffusion approximation breaks down depending on the inclination angle between the magnetic field and the shock normal (Bell et al. 2011). This effect can account for the spectral index \(\alpha \approx -0.35\) measured in the Serpens radio knots, flatter than the typical value \(\sim 0.5\). On the other hand, a flatter spectral index may result from thermal \((\alpha > 0)\) emission contamination, increasing the flux at 6 cm and flattening the spectrum.

From our analysis of the proper motions of the nonthermal radio knots we found that the jet is precessing and that nonthermal bow shocks are excited only at certain epochs. This leads us to think that most of the time the jet parameters do not meet the necessary conditions to produce efficiently relativistic particles in shocks. Since the bow shocks seem to be excited periodically, we speculate that periodic interactions of the driving source of the jet with a close companion could increase the jet velocity (and maybe also produce a slight increase in the mass-loss rate).

5. CONCLUSIONS

We have presented an analysis of new and archive VLA observations of the triple radio source in Serpens. Our main conclusions can be summarized as follows:

1. The triple source in Serpens presents a clear jet-like morphology with a central source and several outer radio knots. The central source shows a positive spectral index at centimeter wavelengths consistent with partially optically thick thermal free-free emission, in good agreement with typical radio jets found in other YSOs. In contrast, the outer knots in the jet, tracing out the movement of the jet through the surrounding medium, show negative spectral indices. This suggests the presence of synchrotron emission, and consequently that a mechanism responsible for particle acceleration up to relativistic velocities might be taking place in these shocks.

2. We measured proper motions for the outer knots and found projected velocities of 200–300 km s\(^{-1}\). These radio knots are most probably tracing shocks of the jet against the dense ambient medium. All this implies that the jet velocity should be high compared with typical velocities in other protostellar jets.

3. Linearly polarized emission is not detected in the radio knots showing negative spectral indices. We estimated upper limits for the polarization degree of \(\sim 10\%\). There are two possible explanations for this low polarization degree: (1) the magnetic field at the jet termination shocks is disordered, or (2) a high electron density in the shocks results in a strong Faraday depolarization of the synchrotron emission.

4. The change in direction of the proper motions of the radio knots suggests precession of the jet. Moreover, their kinematic ages also suggest that they were ejected episodically every 20–30 yr. These results could suggest the presence of a companion orbiting the driving source of the radio jet. If this is the case, we estimated a separation of \(\sim 3\) AU for this binary system.
5. Given that the synchrotron emitter remains unresolved in our 6 cm observations, we conclude that the emission arises in a compact region. Thus, the emission at 6 cm can be produced in the downstream region of the radiative bow shock, or in the jet shocked region. We discuss these two possibilities and conclude that particle acceleration via the Fermi I mechanism can take place only in the Mach disk under certain conditions. We found that the jet must eventually satisfy $M \lesssim 5 \times 10^{-7} \, M_{\odot} \, \text{yr}^{-1}$ and $v_{\text{jet}} \gtrsim 500 \text{ km s}^{-1}$ in order for the Mach disk to be a nonradiative shock and an efficient particle accelerator.

6. Our results on the triple radio source in Serpens indicate that particle acceleration via DSA could be possible in jets from intermediate-mass protostars. The jet does not need to show very extreme characteristics, such as a high mass-loss rate, but it seems to be only necessary that the jet reaches moderately high velocities ($\sim 600 \text{ km s}^{-1}$) at certain epochs. Interactions with the proposed close binary companion could result in episodic increase of the jet velocity and the production of synchrotron emission in the shocks against the ambient medium.

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