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LARGE PROPER MOTIONS IN THE REMARKABLE TRIPLE RADIO SOURCE IN SERPENS

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ABSTRACT

The triple radio source in the Serpens star formation region consists of a central object with a spectral index of $\alpha = 0.1 \pm 0.1$ ($S_\nu \propto \nu^\alpha$) and two lobes with indices of -0.7 ± 0.2 and ≤ -0.6, values that are characteristic of nonthermal emission. The source has a nearly symmetric, linear structure and the separation between the outer components is $\sim 10''$. There is also fainter emission between the central object and the outer components. The results of measurements made at the Arecibo Observatory and the VLA indicate that this triple source is probably associated with the Serpens star-forming region and is not, for example, a background extragalactic source. A weak (~ 200 mJy), circularly polarized 1667 MHz OH maser detected at Arecibo has been observed with the VLA and found to coincide in position to within $1''$ with the central source. The position of this central source also falls within the position error ellipsoid of IRAS 18273+0113. Even more remarkably, VLA observations at a wavelength of 6 cm and a resolution of $1''$ made in 1978, 1984, and 1989 clearly show that the outer components are moving away from the central source. The angular motion of each component with respect to the central one, over the 10.8 yr span of our observations, is $1\farcs3 \pm 0\farcs2$, implying velocities of 300 ± 100 km s^{-1} at a distance of 500 ± 200 pc. The association with star formation activity, and the nonthermal spectra and large proper motions of the outer components make the triple radio source in Serpens a very interesting object.

Subject headings: infrared: sources — nebulae: general — radio sources: general — stars: pre–main-sequence

I. INTRODUCTION

The core of the Serpens molecular cloud consists of two dense condensations, separated by about $3'$, that are the site of recent star formation. The southeast condensation is associated with an optical and infrared reflection nebula (Strom, Grasdalen, and Strom 1974; Gómez de Castro, Eiroa, and Lenzen 1988). The northwest condensation has associated with it two H_2O masers (Rodríguez *et al.* 1980; Haschick *et al.* 1983), a compact, triple radio continuum source (Rodríguez *et al.* 1980; Snell and Bally 1986), peaks in the ammonia (Ho and Barrett 1980; Little *et al.* 1980; Ungerechts and Güsten 1984) and far-IR (Harvey, Wilking, and Joy 1984; Zhang *et al.* 1988) emission, and a molecular outflow (Bally and Lada 1983; Allen *et al.* 1988). Harvey, Wilking, and Joy (1984) suggested that the triple radio continuum source could represent a bipolar, collisionally ionized H II region around a single pre–main-sequence object. On the other hand, extragalactic triple radio sources are not uncommon so that a detailed study of the source was required to establish its nature. For this purpose, we undertook matching-beam observations at 6 and 2 cm wavelength of the source with the Very Large Array (VLA) of the NRAO.[6] We also measured the position of the OH maser, known to be near the Serpens object, with the VLA. We describe the observations in § II, and we present our conclusions in § III.

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II. OBSERVATIONS

We made the observations at 6 and 2 cm wavelength during 1984 January 6 using the VLA, then in the B configuration. To obtain similar angular resolution, $\sim 1''$, at 6 and 2 cm wavelength, we split the array into two subarrays. The first one, consisting of the four outer antennas of each arm, was used for the 6 cm observations. The second subarray, formed by the five inner antennas of each arm, was used for the 2 cm observations. The observations were made with an effective bandwidth of 100 MHz, and the data were edited and calibrated following the standard VLA procedures. In Figure 1 we show the 6 and 2 cm wavelength maps made by the procedures in program MX of Fourier transformation of the calibrated visibilities and application of the CLEAN algorithm. In Table 1 we list the positions, flux densities, and spectral indices of the three dominant components of the radio continuum source. Based on the measurements at two wavelengths, we find that the central source has a spectral index $\alpha = 0.1 \pm 0.1$ ($S_\nu \propto \nu^\alpha$), the NW lobe has $\alpha = -0.7 \pm 0.2$, and the SE lobe was not detected at 2 cm wavelength, so that $\alpha \leq -0.6$. The spectral indices of the outer components suggest that the emission is nonthermal. The three components show structure at the level of $1''$. The separation between the outer components is $\sim 10''$, and at 6 cm wavelength there appears to be fainter emission between the central object and the NW component.

The triple radio source in Serpens might be an extragalactic source projected by chance on the core of the Serpens star-forming region. However, the preponderance of the evidence indicates that it is in our Galaxy. The central component of the triple radio source is within the position error ellipsoid of IRAS 18273+0113, also known as S68 FIRS 1 (Harvey, Wilking, and Joy 1984). The total luminosity of IRAS 18273+0113 is estimated to be 300 $L_\odot$ (Harvey, Wilking, and Joy 1984), equivalent to that of a ZAMS B7 star. The *a priori*

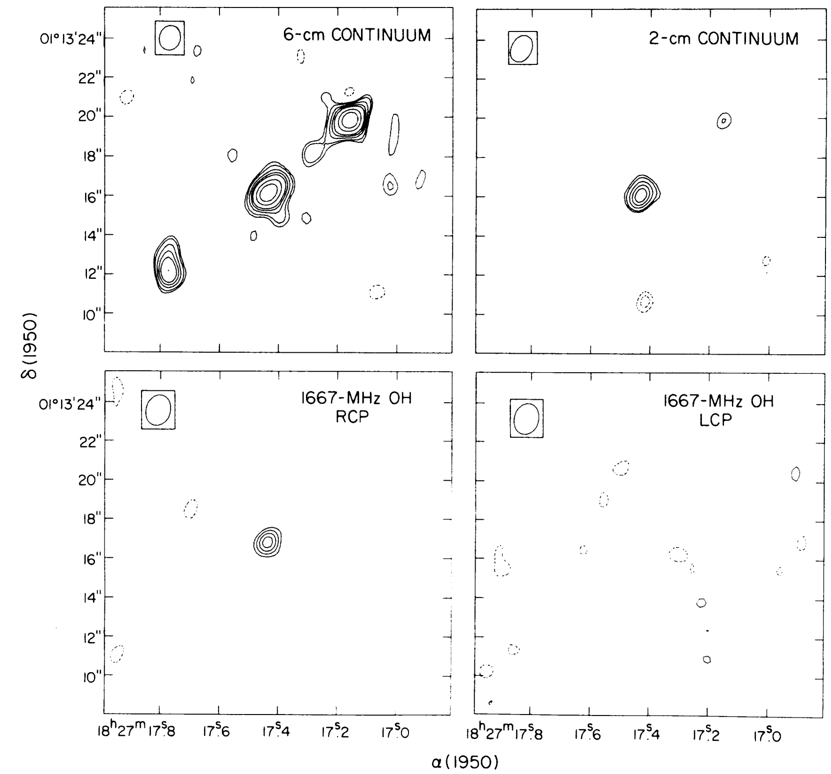

FIG. 1.—VLA map of the continuum and OH emission in the Serpens region. *Top left:* Natural-weighted 6 cm wavelength map. Contours are −3, 3, 4, 6, 8, 10, 15, and 20 times 80 μJy beam^{-1}. *Top right*: Natural-weighted 2 cm wavelength map. Contours are −4, −3, 3, 4, 6, 8, and 10 times 260 μJy beam^{-1}. *Bottom left*: Natural-weighted map of the right circularly polarized 1667 MHz OH emission. The LSR velocity and channel width are 9.5 and 0.27 km s^{-1}, respectively. Contours are −3, 3, 4, 5, and 6 times 18 mJy beam^{-1}. *Bottom right*: Same as bottom left but for the left circularly polarized emission.

probability of finding a 6 cm wavelength extragalactic source of 3.6 mJy within the error ellipsoid of IRAS 18273+0113 is only about 0.0006. Another result suggesting that the triple radio source is in the Serpens cloud is that it has a similar orientation (position angle of about 130°) as that of seven nebulous objects in the region studied by Gómez de Castro, Eiroa, and Lenzen (1988). As part of an OH study of star-forming regions made at the Arecibo Observatory (Mirabel *et al.* 1987), we detected weak (∼200 mJy), right circularly polarized 1667 MHz OH maser emission in the direction of the triple radio source. This OH maser emission is confined to one narrow unresolved feature (≤0.3 km s^{-1}) which is centered at

TABLE 1

OBSERVATIONS AT 6 AND 2 CENTIMETER WAVELENGTH OF THE TRIPLE SOURCE IN SERPENS[a]

Source Component	α(1950)[b]	δ(1950)[b]	Flux Density[c] 6 cm (mJy)	2 cm (mJy)	Spectral Index
NW lobe	18ʰ27ᵐ17ˢ.16	01°13′19″.8	2.7	1.3[d]	−0.7 ± 0.2
Central	18 27 17.44	01 13 16.2	3.6	4.1	0.1 ± 0.1
SE lobe	18 27 17.77	01 13 12.2	1.6	≤0.8[e]	≤ −0.6

[a] Data taken on 1984 Jan 6.

[b] From 6 cm wavelength data. Positional errors are 0″.2. The phase reference source was 1730−130.

[c] The flux density calibrator was 3C 286 (7.41 Jy at 6 cm wavelength and 3.4 Jy at 2 cm wavelength).

[d] Marginal detection.

[e] 3 σ upper limit.

v_{LSR} = 9.5 km s^{-1}. The radial velocity of the ambient cloud is v_{LSR} = 8.1 km s^{-1} (Ho and Barrett 1980). Using the VLA in the A configuration during 1988 October 21, we observed the 1667 MHz transition of OH in both senses of circular polarization. In agreement with the Arecibo results, we detected emission only in the right circular polarization channel (see Fig. 1). We did not detect any continuum emission at a 4 σ level of ∼10 mJy. The position of the OH maser, α(1950) = 18ʰ27ᵐ17ˢ.44; δ(1950) = 01°13′16″.8, coincides within 1″ with that of the central component of the radio triple. This result further supported that the triple source was indeed part of the Serpens star-forming region. The appearance of a single circularly polarized component suggests that the magnetic field has a strength of at least 1 mG, which is sufficient to cause a Zeeman splitting equal to the line width.

We noted that the position of the outer components in our 6 cm map made in 1984 appeared to have moved away from the center with respect to the position obtained in our 6 cm wavelength map made from VLA data taken in 1978 June 19 (Rodríguez *et al.* 1980). To confirm these possible proper motions, we reprocessed the 1978 data with improved algorithms and obtained new 6 cm wavelength, VLA B data during 1989 March 4. In Figure 2 we show the maps for the three different epochs. The three data sets were derived from VLA configurations having similar maximum baseline length (∼10 km). The 1978 and 1989 maps were cleaned and restored with a circular Gaussian beam with a FWHM of 1″.2. In Figure 2, it is evident that, while the central component has the same position, the outer components have moved farther away from the central component. For the 10.8 yr span of our observations,

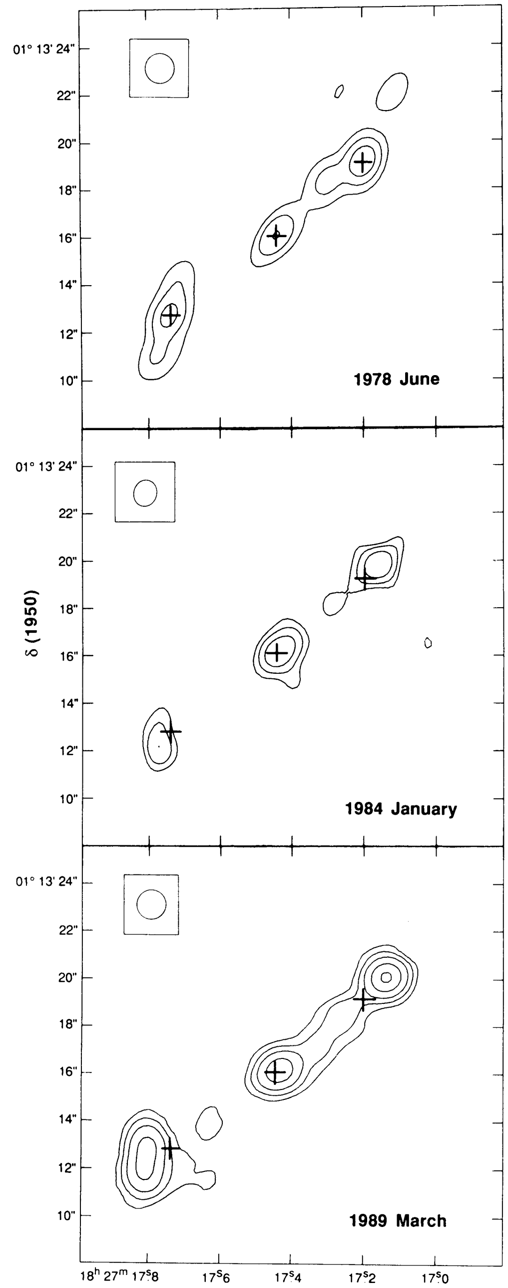

FIG. 2.—Natural-weighted, cleaned VLA maps at 6 cm wavelength of the triple radio source in Serpens. The epoch of the observation is given in each frame. The crosses mark the position of the peak emission of the three dominant components in 1978 June 19. Note the angular displacement of the outer components. Contours are −4, 4, 8, 15, 30, and 50 times 70 (*top*), 80 (*middle*), and 35 μJy beam^{-1} (*bottom*).

the average angular motion of each of the outer components is 1″.3 ± 0″.2, implying tangential velocities of 300 ± 100 km s^{-1} at a distance of 500 ± 200 pc (the average of the distances given by Strom, Vrba, and Strom 1976, Chavarría *et al.* 1988, and Zhang *et al.* 1988). The kinematic age of the expansion is only ~50 yr.

Near-infrared images of the area were obtained on 1988 May 23 on the 1.5 m telescope of CTIO,[7] through a *K* filter, using an 58 × 62 InSb imager with a pixel size of 0″.92 and an approximate field of view of 1′. The resulting images were obtained by subtracting a 300 s exposure "on-object" and a similar exposure on nearby sky. Two similar images were added and the resulting image was median-filtered in order to compensate for possible misalignments introduced in the sum, since no bright feature was present in the images for accurate registration. A contour plot of the resulting image is shown in Figure 3. Similar observations in the *J* and *H* filter yielded no detectable sources. From the *K* band images two sources are clearly visible, surrounded by extended, elongated emission. The alignment of the near-infrared sources follows approximately that of the radio sources. Approximate magnitudes derived from aperture photometry, yield *K* magnitudes of 14.7 and 14.9 ± 0.5 for the two brightest sources (SE and NW, respectively) shown in Figure 3, with $(H-K) \geq 1$ [more sensitive results indicate $(H-K) \geq 3$]. Approximate positions (epoch 1950) for the two brightest sources are $\alpha = 18^h27^m17^s.0$; $\delta = 01°13′27″$ and $\alpha = 18^h27^m16^s.7$; $\delta = 01°13′35″$ with positional errors of about 3″. Since no flux was detected through the *H* filter, the extinction is probably very high and increases towards the radio triple. The near-infrared sources may be related to older ejecta which, as they move toward a region of lower extinction, become detectable at shorter wavelengths. However, our observations cannot distinguish between a reflection or an emission nature. This infrared source has also been observed by Eiroa (1989). Near-infrared nebulae of similar morphology have been found in NGC 1333 (Castelaz *et al.* 1986), the Ophiuchus dark cloud (Castelaz *et al.* 1985), and in association with the H_2O maser near HH 1 (Roth *et al.* 1989).

III. CONCLUSIONS

The bipolar proper motions observed in the triple radio source in Serpens imply tangential velocities of ~300 km s^{-1}, a value similar to those found in some Herbig-Haro objects (Herbig and Jones 1981; Jones 1983). The source is also embedded in a complex molecular outflow (Allen *et al.* 1988)

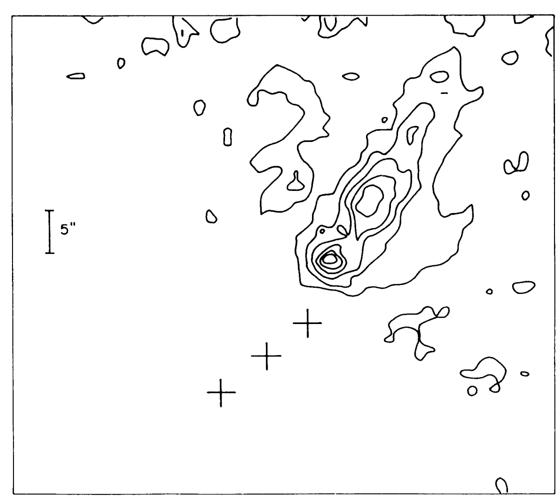

FIG. 3.—Contour map at 2.2 μm wavelength of the elongated nebula to the NW of the triple radio source. The *K* magnitude of the brightest component is 14.7 ± 0.5. The crosses mark the positions of the components of the triple radio source shown in Figs. 1 and 2 in 1984. The positional uncertainty of the infrared image is ~3″.

[7] The Cerro Tololo Inter-American Observatory is operated by AURA under contract with NSF.

and could be the energy source for this outflow. These results, in addition to the association with an OH maser and far-infrared emission, suggest that the central component of the Serpens triple is a heavily obscured pre–main-sequence star undergoing strong mass loss. Sources with these characteristics are frequently found in star-forming regions. The spectral index of the central radio component, $\alpha = 0.1 \pm 0.1$, is similar to those found for the exciting sources of L1551 ($\alpha = 0.0 \pm 0.2$; Rodríguez *et al.* 1989*a*) and HH 1–2 ($\alpha = 0.3 \pm 0.1$; Rodríguez *et al.* 1989*b*). However, the triple source is unique in that its lobes exhibit spectral indices characteristic of optically thin synchrotron emission (note that an inhomogeneous thermal source with a power-law distribution of density cannot produce a spectrum with an index of < -0.1; e.g., Panagia and Felli 1975). Using an angular diameter of 1″ for the lobes and assuming equipartition of energy between the magnetic field and the relativistic electrons, equal density of electrons and protons, and that emission at the observed power law spectral extends from 10 MHz to 100 GHz, we estimate a magnetic field of ~ 1 mG and a minimum energy in relativistic electrons of $\sim 10^{40}$ ergs (e.g., Longair 1981 and Verschuur and Kellermann 1988). The minimum energy is several orders of magnitude lower than those derived by Reynolds and Chevalier (1984) for the nova GH Per ($E_{\rm min} \sim 10^{43}$ ergs) and the four young supernova remnants Cas A, Tycho, Kepler, and SN 1006 ($E_{\rm min} \sim 10^{48}$ ergs).

The emission at 6 cm wavelength is produced by electrons with a Lorentz factor of about 10^3. The production of relativistic electrons in the environment of pre–main-sequence objects is not easily explained. While in evolved, collapsed objects there are very large gravitational potentials capable of accelerating particles to relativistic velocities, in pre–main-sequence objects the gravitational potentials are modest and velocities of a few hundred km s^{-1} are expected. Perhaps a particle acceleration mechanism involving shocks of similar nature to that proposed for supernova remnants by Bell (1977) and Blandford and Ostriker (1978) is at work.

There are other known sources with associated synchrotron emission that may be pre–main-sequence objects. G70.7+1.2, a shell-like nebula embedded in a molecular cloud, has a polarized, nonthermal radio spectrum and its identification as a nova, supernova, or outflow remains controversial (Reich *et al.* 1985; de Muizon *et al.* 1988; Becker and Fesen 1988; Bally *et al.* 1989). A similar radio spectrum is found for the Herbig-Haro–like filament near V571 Ori (Yusef-Zadeh, Cornwell, and Reipurth 1989). Other nonthermal double and triple radio sources have been found in regions of star formation (Rodríguez and Cantó 1983; Schwartz, Frerking, and Smith 1985; Snell and Bally 1986).

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