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DETECTION OF SYNCHROTRON EMISSION FROM A UNIQUE HH–LIKE OBJECT IN ORION

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ABSTRACT

VLA observations of an HH–like object, known as the Orion "streamers" in the L1641 cloud, have been carried out at λ2, 6, and 20 cm. This object is located several arcminutes to the north of HH 34 and exhibits a unique morphology which consists of a long and narrow structure with approximate dimensions of 10″ × 300″ in optical photographs. We have detected a significant linearly polarized emission at λ6 cm arising from near the core of the streamers, indicating uniform magnetic field geometry. This result suggests that the source responsible for producing the nebulosity is a nonthermal-emitting radio source. Because of the presence of a number of newly born low-mass stars in the vicinity of the streamers and because of the detection of a faint highly reddened 2 μm source coincident with the polarized radio emission, we believe that the source at the core of the streamers is a low-luminosity young star responsible for both the synchrotron emission and the shock nebulosity. The large-scale linearly polarized stellar emission implies that the magnetic field is highly ordered surrounding the star and that a rotating magnetosphere may be responsible for global acceleration of particles as a result of the reconnection of the field lines in the outer magnetosphere along the equatorial region.

Subject headings: infrared: sources — magnetic fields — radiation mechanisms

I. INTRODUCTION

Detailed structure of the Orion streamers was recently examined by Reipurth and Sandell (1985, hereafter RS). The streamers lie a few arcminutes north of the spectacular HH 34 in Orion and adjacent to a T Tauri star, V571 Ori, ~20″ from the brightest portion of the streamers. These authors find that the nebulosity of the streamers has a unique morphology with a number of arclike structures emanating from its central core and shows an HH–like spectrum with prominent Hα, [N II], and [S II] emission lines with very little scattered light from its central portion. RS searched in vain for an embedded driving source. In the absence of an internal energy source, they then suggested that the HH–like nebulosity seen in the streamers is a shock front caused as a result of the interaction between the stellar wind emanating from V571 Ori star and the edge of an adjacent molecular cloud.

In this *Letter* we report the discovery of linearly polarized emission at radio wavelengths and the detection of a 2 μm source close to the core of this shock region. We argue that the source responsible for the excitation of this region is a synchrotron-emitting low-luminosity star.

II. OBSERVATIONS AND RESULTS

Radio continuum observations were carried out on 1987 May with the VLA in its compact D-configuration at λ6 cm. Follow-up observations were carried out at λ6 and 20 cm in the C-array in 1988 April and at λ2 cm in the D-array in 1988 September. The visibility data were calibrated in all observing sessions by using 3C 48 and 0539−057 as the amplitude and phase calibrators. 3C 48 was assumed to have a flux density of 15.37, 5.36, and 1.85 Jy at 1.465, 4.885, and 14.965 GHz. The cross-hand polarization angle was determined by observing 3C 138. The polarization calibration was made by using 0539−057 during each observing session which lasted for ~10 hr. The visibility data were calibrated in the standard manner. The λ6 cm data corresponding to C- and D-array configurations were combined before the final map, as shown in Figure 1 (Plate L2), was constructed. The spectral index measurements between the λ6 and 2 cm flux densities are based on scaled array observations where the two data sets have similar spatial resolutions and are sensitive in bringing out the same scale structures.

The infrared observations were performed on the night of 1988 October 24 on the 4 m telescope at CTIO IR imager consisting of 62 by 58 InSb elements with pixel size ~0″.31. Rotation of the detector was verified to be less than 1 pixel for a complete scan of a star across the detector in declination. The pointing was done by offsetting from V571 Ori, using the coordinates and positions as given by RS.

Five 60 s integrations "on object" were averaged. The same number of integrations taken 40″ to the south were used in each case, as "sky" frames. V571 Ori was used for autoguiding. The averaged raw frames were dark-subtracted and corrected for a small nonlinearity. Sky frames taken imme-

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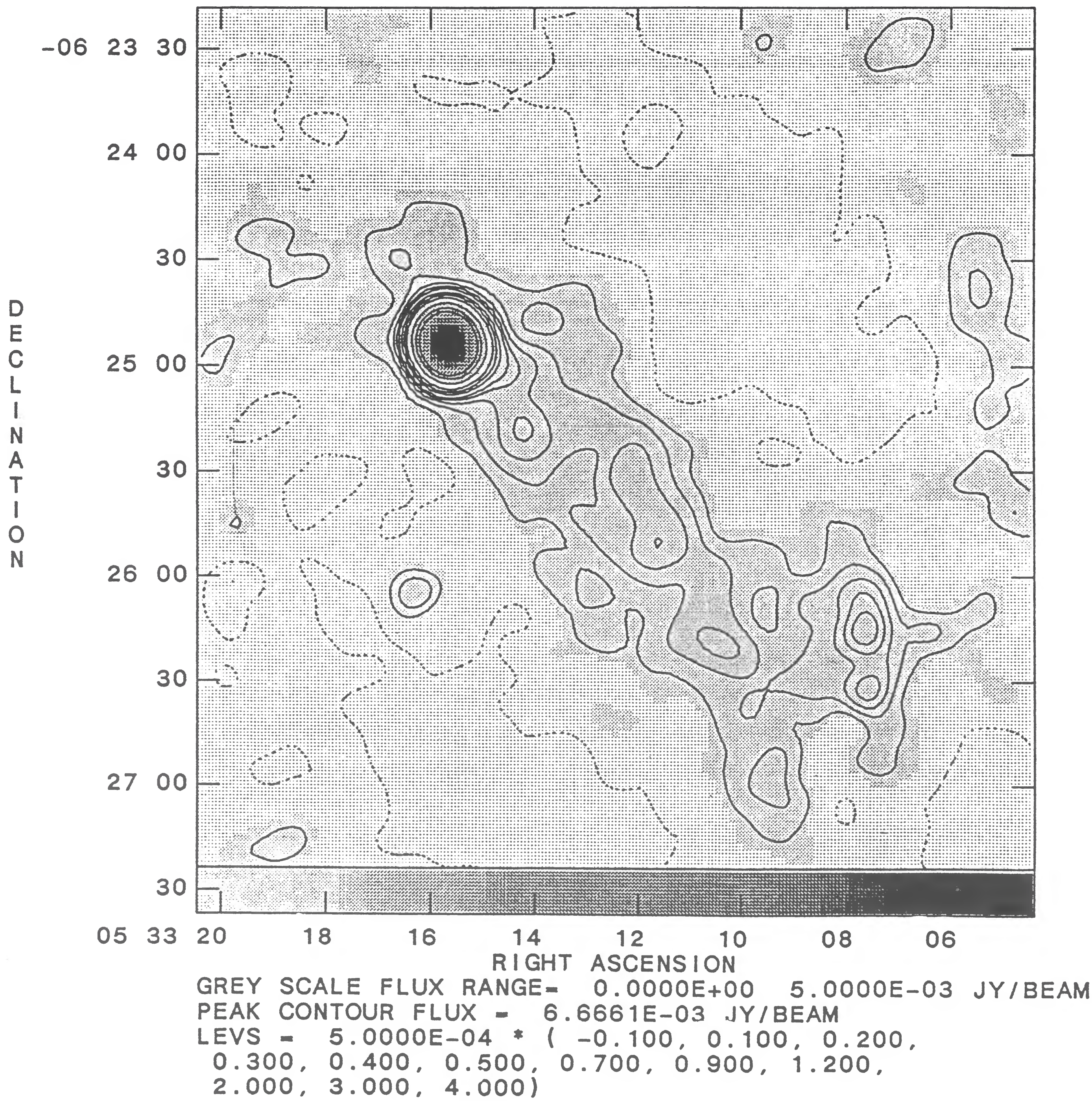

FIG. 1.—The λ6 cm map of the streamers with a spatial resolution of 12″ × 12″. Contours are set at −0.05, 0.05, 0.1, 0.15, 0.2, 0.25, 0.35, 0.45, 1.2, 2, 3, 4 mJy. The peak flux is 6.6 mJy per beam area.

YOSEF-ZADEH *et al.* (*see* **348**, L61) diately after the "object" frames were then subtracted from these, in order to cancel the sky contribution and to correct for a few bad pixels. No further processing was performed on these images.

Figure 1 shows the continuum map of the streamers at λ6 cm with a spatial resolution of ~12″ × 12″. The region of the streamers contains a discrete compact radio source from which elongated nebulosity appears to arise as it extends for about 2′ due southwest. The compact component lines near the core position of the optical streamers (see below) from which a number of arclike structures appear to emanate (RS). In spite of the low spatial resolution, the radio continuum extended structure with surface brightness of ~0.1–0.2 mJy beam^{-1} resembles a similar morphology to that of the elongated 5′ optical structure seen as arc A in the optical image of this source (RS). The λ6 cm map is sensitivity-limited because of the strong source as described above; thus much of the weak and extended nebulosity seen in Hα images is not brought out. Consequently, we were not able to determine the spectrum of the radiation associated with the extended structure. Based on the emission measure calculations, we estimate that the average electron density is 55 cm^{-3} by assuming that the radiation has thermal characteristics, the emission arises from spheres with a linear diameter of ~0.15 pc, and that the typical flux density at 5 GHz is 0.15 mJy per beam area. The derived value is a lower limit to the actual electron density since the source angular size could be lower than 12″ × 12″, as assumed here.

We detected a significant degree of linear polarization, 6%–8%, at the position of the compact source at λ6 cm, as shown in Figure 2. We note the elongated morphology of the total and polarized intensity distributions is directed along the major axis of the extended optical nebulosity. The highest degree of polarization appears to arise from the central region of the discrete source surrounded by a halo of depolarized emission. The λ2 cm continuum map of the core region is presented in Figure 3 and shows again a geometrical alignment in the direction of extended optical emission. The λ2 cm emission breaks up into two components along the major axis of the core radio source. The extended nebulosity is resolved out in this map, and the two compact components remained partially unresolved. The parameters of a multiple-Gaussian fit to the central source at both λ6 and λ2 cm are listed in Table 1. No significant linearly polarized emission was detected to a limit of ≥20% at λ2 cm, and no circular polarization was detected at λ2 cm.

Spectral index measurements based on peak fluxes at λ6 and 2 cm indicate that the northeastern (NE) component has $\alpha \sim -1.1$, where $F_\nu \propto \nu^\alpha$, and is steeper than that of the southeastern (SE) component with $\alpha \sim -0.8$. A steep value of $\alpha \sim -1.2$ is also found when the comparison was made

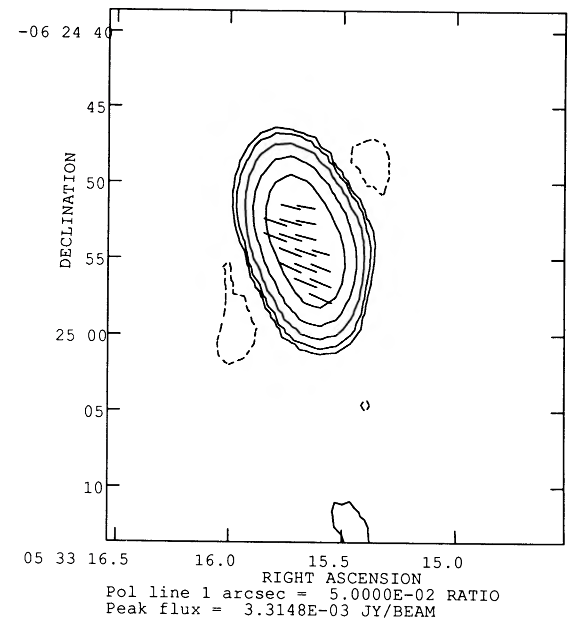

FIG. 2.—The high-resolution map of the core of the streamers with a resolution of 4″.8 × 3″.4 (PA = −7°) is shown with contours of total intensity at λ6 cm set at −0.11, 0.11, 0.19, 0.37, 0.7, 1.5 mJy per beam area. The orientation of the line segments correspond to the direction of electric field vectors, and their lengths are proportional to the degree of linear polarization. The line segments with a length of 1″ correspond to 5%.

between the λ20 and 6 cm maps with a spatial resolution of 18″.3 × 11″.1. The λ20 cm peak flux of 16.9 mJy beam^{-1} is a few times higher than that seen toward HH 1 and HH 2 in Orion. No significant polarized emission was detected at λ20 cm. Figure 4 shows the superposition of the λ2 cm map on contours of Hα emission and indicates a displacement of ~10″ between the peak radio and optical positions. The appearance of a northwestern protrusion in the radio map may be related to the peak optical emission which is elongated toward it.

The *J*, *H*, and *K* observations revealed two weak sources, IRS 1 and IRS 2, in the core region. The coordinates and near-IR magnitudes of these sources are listed in Table 2, and their positions are indicated by crosses in Figure 4. The position of IRS 1 within the uncertainty coincides with the peak SW radio component.

III. DISCUSSION

Detection of steep-spectrum, linearly polarized radio continuum emission suggests strongly that the radiation from the core of the streamers is produced by the sychrotron mechanism and that the emitting electrons have energies ≥100 MeV. Due to the large Faraday depolarization seen toward this

TABLE 1

GAUSSIAN FITTING PARAMETERS OF THE COMPONENTS IN THE STREAMER

Name	α(1950)	δ(1950)	Peak Flux (mJy) 2 cm	Peak Flux (mJy) 6 cm	Integrated Flux (mJy) 2 cm	Integrated Flux (mJy) 6 cm[a]	Size 2 cm[b]
NE.........	$5^h33^m15^s.78 \pm 0.01$	$-6°24'51''.69 \pm 0''.24$	0.77	2.78	1.56	3.5	6.1″ × 3.25″
SW.........	5 33 15.62 ± 0.01	−6 24 54.72 ± 0.21	1.01	2.55	0.85	3	6.6 × 4.2

[a] FWHM = 4″.78 × 3″.39.
[b] FWHM = 4″.29 × 4″.20.

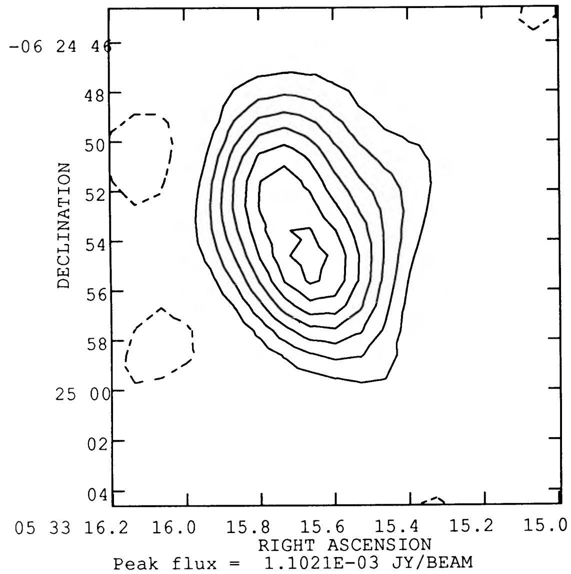

FIG. 3.—The λ2 cm continuum map with a resolution of 4″.3 × 4″.2. Contours are set at −2, 2, 4, 6, 8, 10, 12, 14 times the rms noise level which is 7.3×10^{-5} Jy per beam area.

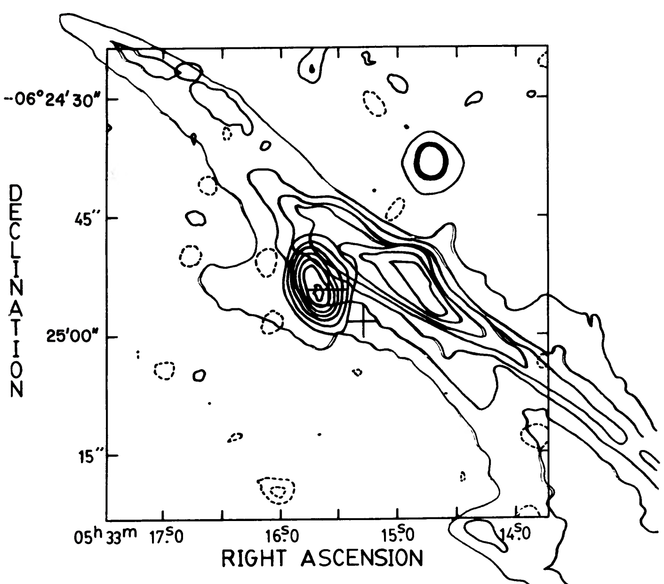

FIG. 4.—The λ2 cm continuum map of Fig. 3 superposed on contours from an Hα CCD image. The thick black circle to the upper right represents V571 Ori. The crosses show the positions of 2 μm sources, IRS 1 and IRS 2.

source, as evidenced by the lack of linear polarization at λ20 cm, the present radio data are not sufficient to determine the intrinsic orientation of the magnetic field. However, due to a significant degree of linear polarization, the magnetic field has to be organized on a scale of 2500 AU. An estimate of the magnetic field in the synchrotron-emitting region can be derived using the equipartition of energy between electrons and the magnetic field. We estimate that the minimum magnetic field, $B_{\rm min}$, at the position of maximum intensity is $\sim 5 \times 10^{-4}$ G. In this calculation we assumed that the radio spectrum has a power-law distribution which extends from 10^7 MHz and 10^{11} Hz, the mean $\alpha = -1$, the total radio luminosity of 4.5×10^{28} ergs $\rm s^{-1}$ arising from a radius of the deconvolved half-width at half-maximum (HWHM) of 4″.25 at the position of maximum flux at λ2 cm.

IRS 1 is coincident with the brighter of two radio components and is probably a low-luminosity star embedded in the L1641 cloud. Molecular observations as reported by RS suggest that the streamers are associated with a cloud in the Orion region and, therefore, strengthen the above suggestion that IRS 1 is a pre–main-sequence object. The *IRAS* Point Source Catalog shows no source close to the core of the streamers. However, because of the extended infrared emission, it is difficult to identify point sources in this region (Strom *et al.* 1986). We are not able to estimate the luminosity of IRS 1 accurately without mid- and far-infrared photometry; in the limited range 1.2–2.2 μm, the luminosity is less than 0.002 $L_\odot$ without taking extinction into account. This, then suggests that the synchrotron emitting source is unlikely to be associated with a massive OB star and that a low-luminosity pre–main-sequence star is probably responsible for the origin of the streamers rather than V571 Ori or IRS 5 (RS; Cohen and Schwartz 1983).

There is considerable observational and theoretical evidence that stellar winds in massive stars have embedded shocks which can accelerate particles to relativistic energies (Blandford and Ostriker 1987; White 1985; Abbott *et al.* 1985). However, it is unlikely that this mechanism can explain the large-scale magnetic structure implied from polarization characteristics. Lack of time variability in polarized and total intensities from the streamers in two epochs which we observed with the VLA rules out the possibility that the emission is due to flare activity on the surface of the star. This, plus the fact that polarized emission appears to be associated with a 2 μm source, argues in favor of a permanent field configuration surrounding a magnetic pre–main-sequence star. We sketch below a qualitative model to explain the observed synchrotron phenomenon from a pre–main-sequence star.

We consider that the energetic particles are accelerated globally in the outer region of a rotating magnetosphere surrounding a mass-losing star. It is conceivable that the geometry of the magnetic field, *B*, is dipolar near the surface of the star. The combined effects of the rotation of a pre–main-sequence star

TABLE 2

THE NEAR-IR SOURCES[a]

Name	α(1950)	δ(1950)	J	H	K
IRS 1(NE).........	$5^h33^m15^s.6$	−6°24′54″	≥20.0	17.7 ± 0.4	16.04 ± 0.1
IRS 2(SW).........	5 33 15.3	−6 24 59	>20.0	19 ± 1	16.9 ± 0.3

[a] Absolute positional uncertainty of ±1″.5.

and of stellar wind outflow threaded by the magnetic field lines distort the magnetic field lines in the magnetosphere to such an extent that a magnetodisk is formed in the outer magnetosphere along the equatorial region. It is in the magnetodisk region where the plasma can be accelerated to relativistic regime as a result of steady state reconnection of the field lines. Recent numerical work by Goldstein, Mathaeus, and Ambrosiano (1986) supports the view that a significant fraction of charged particles can be accelerated to high energies. This global acceleration mechanism in the outer region of the magnetosphere near the Alfvén surface where the ordered field lines have a radial dependence is needed to explain the significant linear polarization observed in radio wavelengths. A similar magnetospheric model has also been invoked to explain the nonvariable circular polarization detected from a young peculiar B star in the Rho Ophiuchi cloud (André *et al.* 1988).

Alternatively, the evidence for energetic particles and a large-scale magnetic field associated with a HH object may support the earlier model by Uchida and Shibata (1984) who proposed accretion of magnetic materials onto a young star. The production of high-energy particles, as proposed in their model, may occur in a neutral ring where magnetic reconnection occurs and which acts as a means to accrete nebular materials onto a young star and decouple the materials from the magnetic field. They also predict that the mass loss which is directed along the open magnetic field lines may be responsible for the mass outflow and HH nebulosity seen in the vicinity of young stars. It is also possible that the shock region as manifested in the optical emission is produced as a result of the outflow of relativistic gas from an embedded source. In this model some of the energy of outflowing materials which is manifested in the radio continuum emission is dissipated (Yusef-Zadeh and Morris 1987) as it breaks through and impacts the surface of the cloud and shock the gas.

In conclusion, we have found a unique synchrotron-emitting object in the L1641 cloud which coincides with a 2 μm source and which is physically associated with the core of a shock region having a remarkable streamer-like morphology. The presence of synchrotron emission suggests that the magnetic field plays a major role in formation of this object. While we believe that the streamers represent shock generated by a very young star embedded in a well-known star-forming region, we hesitate to call them a Herbig-Haro object in the classical sense, because their size, morphology, and associated synchrotron phenomenon deviate significantly from characteristics of normal HH objects. Future high-resolution spectroscopic, molecular, X-ray and linear polarization measurements are essential to further understanding of this unusual object.

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