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THE STAR-FORMING REGION IN CEPHEUS A

V. A. HUGHES
Astronomy Group, Department of Physics, Queen's University at Kingston, Ontario, Canada

AND

J. G. A. WOUTERLOOT
Sterrewacht, Leiden, The Netherlands
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ABSTRACT

Observations have been made of the molecular cloud condensation Cep A, with resolutions down to 1″ at 21 cm and 6 cm, using both the Westerbork Synthesis Radio Telescope, and the NRAO Very Large Array. The condensation is seen to contain two strings of H II regions, which are interpreted as being produced by about 14 stars, each of which mimics main-sequence B3 stars; the length of each string is about 0.1 pc. The H II regions are very young, $\sim 10^3$ yr old, and it is suggested that the environment is controlled by a magnetic field.

Subject headings: interstellar: molecules — nebulae: H II regions — nebulae: individual — stars: formation

I. INTRODUCTION

It is well known that stars form in molecular clouds, but the initial stages of star formation have been difficult to observe optically because of heavy obscuration. At radio wavelengths, it is possible to measure the flux from the associated H II regions, and provided that the region is ionization limited, to determine the Lyα output, and thus the spectral type and luminosity of the exciting stars. Suitable stellar models are required (e.g., Panagia 1973), and the individual regions must be resolved. A number of regions in IC 1795/1805 have been checked, and it was found that the luminosity of the star derived in this way is approximately equal to the measured total infrared radiation from the surrounding molecular cloud, which peaks near 100 μm (Hughes and Vallée 1978). This was as expected since though only the Lyα leads to the production of the H II region, most of the total radiation is absorbed in the cloud. Small individual infrared sources detected at 20 μm are probably due to pre-main-sequence objects.

The Cep A condensation in the much larger molecular cloud discovered in CO by Sargent (1977, 1979) appeared to be a further region of particular interest since it showed the presence of thermal emission (Harten, Thum, and Felli 1981), OH and H_2O emission (Blitz and Lada 1979; Norris 1980; Wouterloot, Habing, and Herman 1980; Lada *et al.* 1981), both indicative of star formation, and a far-infrared luminosity of $2.5 \times 10^4\ L_\odot$ (Koppenaal *et al.* 1979; Beichman, Becklin, and Wynn-Williams 1979; Evans *et al.* 1981) which was attributed to internal heating of the cloud by stars. In addition, a few compact H II regions were resolved using the VLA of the National Radio Astronomy Observatory[1] (Beichman, Becklin, and Wynn-Williams 1979; Rodriguez *et al.* 1980); nearby was a suspected Herbig-Haro object GGD 37 (Gyulbudaghian, Glushkov, and Denysiuk 1978); and anisotropic mass outflow was observed in CO (Rodriguez, Ho, and Moran 1980), NH_3 (Brown *et al.* 1981), and HCO^+ (Sandqvist *et al.* 1982). Some initial observations were made with the Westerbork Synthesis Radio Telescope (WSRT)[2] at 21 cm, which showed that there were two main H II regions (Hughes and Wouterloot 1982; Hughes, Viner, and Wouterloot 1982), but when the more easterly one, which was the region of the previous VLA observations, was observed also at 6 cm, it appeared to consist of a much larger number of compact regions than had been suspected previously, because the VLA observations were limited by sensitivity to about 1 mJy per beam. We have taken further observations with the VLA down to a sensitivity of about 0.15 mJy per beam and resolution of 1″, which show the region to break up into about 14 of the most compact H II regions yet detected and which we believe to be produced by the youngest stars in the densest association of its kind yet discovered. This paper describes the observations, the resulting maps, and the initial analysis of the region. In the ensuing discussion, it is pointed out that it is highly likely that the region is being controled by a magnetic field. The observations do not appear to confirm the model by Ho, Moran, and Rodriguez (1982).

II. OBSERVATIONS

The WSRT observations were made at 6 cm for a total of 12 hr on 1979 May 11. The elements of the array provided a total of 18 interferometers with spacings from 36 m (170λ) to 1260 m (5934λ) in steps of 72 m (340λ). The data was Fourier transformed in the standard way, the CLEAN procedure was used, and the map restored using a Gaussian beam of 7″ × 8″. We thus have information on components

[1] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

[2] The Westerbork Synthesis Radio Telescope is operated by the Netherlands Foundation for Radio Astronomy (SRZW), with financial support of the Netherlands Organization for Pure Research (ZWO).

ranging in size from about 8″ to about 6′. Processing of the data was carried out at Sterrewacht, Leiden.

The VLA observations were made in the B configuration for a total of 12 hr on 1981 July 25/26, and were alternated between 6 cm and 20 cm. The observing sequence was 2 minutes on the reference source BL Lac, 20 minutes on Cep A, and 2 minutes on BL Lac for each frequency. Flux densities of BL Lac were calibrated against 3C 286, assuming its flux densities to be 7410 mJy and 14,770 mJy at 6 cm and 20 cm, respectively. At 6 cm and 20 cm, the restoring beamwidths after cleaning were 1″.2 × 1″.1 and 3″.65 × 3″.35, and the largest structures observable were 11″ and 38″, respectively. To compare fluxes and obtain spectral indices, though at low angular resolution, both cleaned maps were convolved with an equivalent beam of 4″.8 × 4″.8. Most of the extensive reduction was carried out at NRAO, Charlottesville, though some initial processing of the MODCOMP tapes was carried out at Sterrewacht, Leiden, and some of the final reduction at Queen's University.

III. RESULTS

The WSRT 6 cm map of the Cep A region is shown in Figure 1. With the improved resolution of about 7″ at 6 cm, compared with the 30″ of the 21 cm observations (Hughes and Wouterloot 1982), the source to the east shows some fairly complex structure and has been divided into four areas, as shown. Area 3 contains the four compact regions as seen in the results from the VLA at 6 cm (Beichman, Becklin, and Wynn-Williams 1979; Rodriguez *et al.* 1980). The source to the west is associated with optical nebulosity (Hughes and Wouterloot 1982). The extent of the red- and blueshifted features seen in the wings of the CO line (Rodriguez, Ho, and Moran 1980; Ho, Moran, and Rodriguez 1982) are also shown.

The VLA map of the easterly source at 6 cm is shown in Figure 2. It is quite clear that the region is being resolved into a large number of compact components. Maser sources have been observed in the region (Blitz and Lada 1979; Norris 1980; Wouterloot, Habing, and Herman 1980; Lada *et al.* 1981), an OH maser being coincident with source 3c and H_2O masers with sources 2 and 3d; maser sources are normally associated with newly formed H II regions, and we shall argue later that all the sources in the area are H II regions. Of interest is the fact that the regions appear to have formed in two lines, one directed in the NE–SW direction, and the other in a close to E–W direction. The NE–SW line is approximately the direction of the major axis of the CO condensation mapped by Sargent (1977, 1979) and known as Cep A, and it would appear that there is some form of symmetry about this direction; this axis is also approximately parallel to the Galactic equator. Since the deviation of the H II regions from a projected straight line seems to be less than about 2″.5, or less than 1800 AU for the distance of 725 pc (Garmany 1973), and the length of the line is about 40″, or 30,000 AU (0.14 pc), we interpret this to mean that they formed in a line rather than in a disk or plane which is seen edge-on. The reason why two lines of sources exist is not initially evident.

The compact nature of the individual sources can be seen

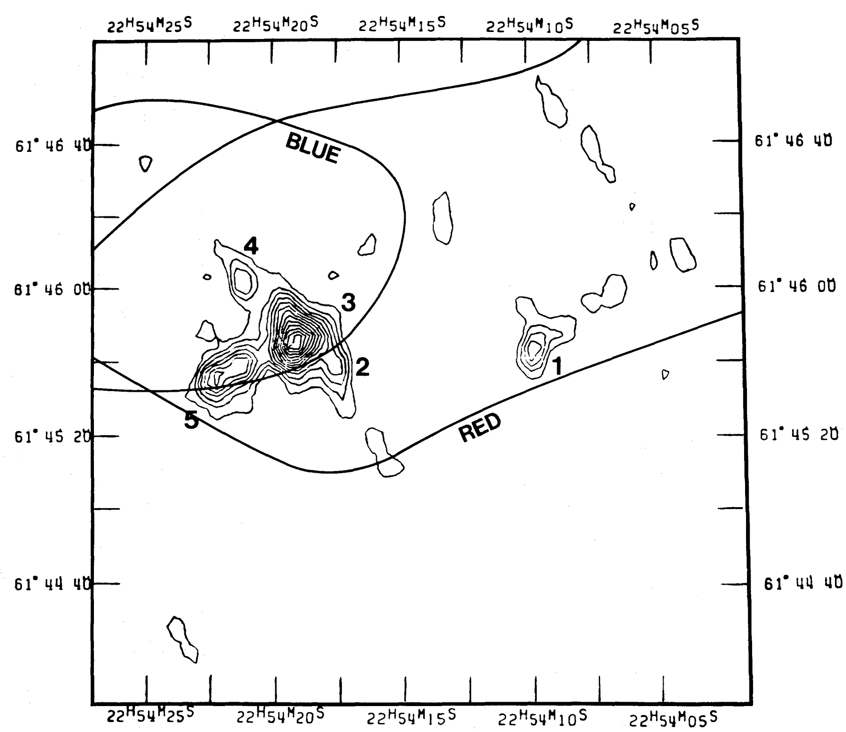

FIG. 1. WSRT 6 cm map of the Cep A region. Source 1 is the westerly source associated with the optical nebulosity; sources 2, 3, 4, and 5 are the H II regions which are optically obscured and assumed to be produced by young stars. Contour intervals are 1 mJy. Beamwidth is 7″ × 8″. Contours are drawn to show the blueshifted (to the east) and redshifted (to the west) components as seen in the wings of CO (Ho, Moran, and Rodriguez 1982).

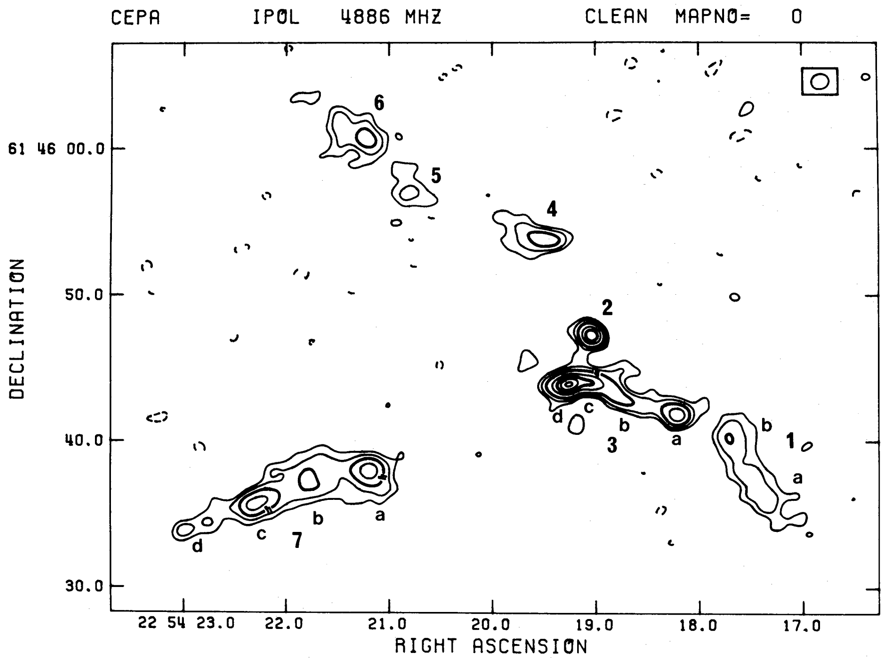

FIG. 2.—VLA map at 6 cm in the "B" configuration of sources 2, 3, 4, and 5 of Fig. 1. The numbered regions are not the same as for Fig. 1 but are identical with those in Table 1. Contour intervals are 0.15, 0.3, 0.6, 1.2, 1.8, 2.4, and 3.0 mJy per beam. Beamwidth is 1″ × 1″ and is indicated in the top right-hand corner.

from the fact that their size on the VLA 6 cm map is not much larger than the 1″ beam, which means a linear size of 725 AU, though some extension can be seen along the same direction as that of the lines.

IV. ANALYSIS OF DATA

The VLA 6 cm and 20 cm maps, both convolved to the beamwidth of 4″.8 × 4″.8, were initially compared to determine the spectral index α, defined by $S \propto \lambda^{-\alpha}$, where S is the flux density, and λ is the wavelength. The only region with a significantly positive value for α was source 2, indicating that it is optically thick at 20 cm, but for the other sources, α was consistent with their being thermal and optically thin. However, most of the sources were not resolved with this beamwidth, and higher angular resolution was required.

Gaussian elliptical sources were then fitted to the VLA 6 cm data, and the results are given in Table 1. In some cases, for example source 7, it was clear that there were four peaks in emission, and thus four components were fitted to the region. For source 3, the presence of two maser sources, normally indicative of H II regions, was used to provide positions for 3c and 3d, and additional peaks in emission showed the presence of components 3a and 3b. Gaussian components were then fitted at the same positions in the 20 cm data, but because of the lower angular resolution, the solutions did not always converge, and values for some individual components were meaningless. In these cases, such as sources 2 and 3, the values for all the components have been combined to give a resultant total flux. For comparison purposes, flux from the same components at 6 cm have been combined, and these are also indicated in Table 1. A comparison of fluxes at the two wavelengths again shows that they are consistent with an origin in thermal emission. Source 2 appears to have a significantly lower flux density at 20 cm that at 6 cm, again indicating that it is optically thick at the longer wavelength. The total flux at 6 cm is 54.4 mJy, and at 20 cm is 62.7 mJy, which are consistent with an origin in thermal sources. The total integrated flux at 20 cm using the WSRT with angular resolution of about 30″, is 71 ± 7 mJy (Hughes and Wouterloot 1982). However, there is the possibility of a low-level diffuse emission in the

TABLE 1

VLA FLUX DENSITIES OF INDIVIDUAL REGIONS

Source	R.A.	Decl.	Flux (mJy) 6 cm	Flux (mJy) 20 cm
1a	22ʰ54ᵐ17ˢ.5	61°45′37″.3	5.8	...
1b	22 54 17.7	61 45 40.5	0.7	...
1a plus 1b			6.5	10.1
2	22 54 19.0	61 45 47.3	3.2	...
3a	22 54 18.2	61 45 41.9	2.6	...
3b	22 54 18.8	61 45 43.3	3.5	...
3c	22 54 19.1	61 45 44.1	2.6	...
3d	22 54 19.3	61 45 43.9	4.8	...
2 plus 3a–3d			16.3	15.5
4	22 54 19.6	61 45 53.8	4.1	6.3
5	22 54 20.8	61 45 56.8	5.5	5.6
6	22 54 21.3	61 46 00.8	4.3	4.2
7a	22 54 21.2	61 45 37.9	3.6	5.0
7b	22 54 21.8	61 45 37.4	7.3	11.0
7c	22 54 22.3	61 45 35.7	4.0	3.0
7d	22 54 22.9	61 45 34.3	2.4	2.2
7a–7d			17.3	21.2
Total			54.4	62.7

latter, which extends over a region of dimension about 1'.5–3', and which encompasses all the sources of Figure 1, including source 1. The flux density per beam is too low to be detected using the much smaller synthesized beamwidths of the WSRT and VLA at 6 cm, but in any case, the 6 cm observations by Harten, Thum, and Felli (1981), made with a 2'.5 beam, indicate that this diffuse emission can add only a small contribution to the total flux density. Since the diffuse level does not appear on the high-resolution maps, the main part of the discussion will be on the contribution by the compact sources.

Thus, we conclude that most of the emission is from H II regions, though the accuracy is such that some contribution could be the result of stellar winds, for instance, which could modify the spectral index by increasing the value of α from what in an ideal case would be 0.1, to 0.6 for the case of a stellar wind (e.g., Purton *et al.* 1982). In any case, we exclude the possibility of the objects being extragalactic.

If the sources are individual H II regions, and are ionization limited, we can determine the parameters of the exciting star. Assuming that the regions are spherical, it can be shown that the excitation parameter, U (pc cm^{-2}), is given by

$$U = 1.41 \times 10^{-2} S^{1/3} D^{2/3} ,$$

where S (mJy) is the flux density at 6 cm and D (pc) is the distance. Assuming that $D = 725$ pc,

$$U = 1.14 S^{1/3} .$$

It it can be assumed that the stars are on the main sequence the luminosity of the exciting star, L, can then be derived from the stellar models by Panagia (1973), and from this the mass of the star, assuming that

$$\log (L/L_{\odot}) = 3.7 \log (M/M_{\odot}) .$$

An initial inspection of the sources shows that though some are more extended than others, the average flux density is 3.7 mJy, and most deviate from this by less than 1 mJy. This gives a typical excitation parameter of 1.8 ± 0.2 pc cm^{-2}, corresponding to a B3 star, for which the luminosity is estimated to be 2.0×10^3 $L_{\odot}$, and mass 7.8 $M_{\odot}$. If the H II regions are not ionization limited, then the inclusion of the possible small diffuse component as seen in the WSRT and Effelsberg data will not significantly change these values.

To demonstrate the limited range in effective spectral type, we estimate that if the stars had been B2, for which $U = 2.6$ pc cm^{-2}, then the expected flux from each region would have been 12 mJy, or if the stars had been B4 ($U = 0.82$ pc cm^{-2}), the flux would have been 0.4 mJy. It is clear that if the individual H II regions are produced by stars, then the stars lie in a very limited range of effective spectral type. However, as we shall see later, the stars may be very young and only mimic these spectral types.

The typical electron density of a region can be obtained from U by assuming that a typical region is 1" in diameter, or a linear diameter of 725 AU. This leads to a value of 3.3×10^4 cm^{-3}. We estimate that for source 2, $N = 8.3 \times 10^4$ cm and $R = 180$ AU, which could indicate a somewhat younger H II region, but the star exciting it is not significantly different from the others in the area.

Some H II regions may not be resolved, so that there is some difficulty in determining the total number, but from Table 1 we estimate a total of 14, which would give a total stellar luminosity of about 2.8×10^4 $L_{\odot}$, in general agreement with the total far-infrared flux from the region of 2.4×10^4 $L_{\odot}$ (Kopenaal *et al.* 1979; Beichman, Becklin, and Wynn-Williams 1979; Evans *et al.* 1981).

Ho, Moran, and Rodriguez (1982) have constructed a model in which the stars associated with the H II regions have blown out a cavity in the molecular cloud, the cavity extending along a NE–SW direction. Such a cavity would contribute a diffuse component of the emission. However, if we assume that there are only three stars in the region, as indicated by the presence of the masers in sources 2 and 3, and the other peaks are caused by clumpiness in these regions, then our total 21 cm flux of 71 mJy could be attributed to three similar stars each with an excitation parameter of 3.1 pc cm^{-2}. These would correspond to B2 stars, each of which would have a luminosity of 3×10^3 $L_{\odot}$, so that the total 100 μm luminosity would be expected to be 10^4 $L_{\odot}$, and significantly less than the 2.5×10^4 $L_{\odot}$ observed. Again, this assumes main-sequence stars with particular model atmospheres, and in any case, this interpretation is very model dependent.

The very young age of the H II regions can be demonstrated from simple considerations. Though the time taken for the stars to turn on their UV radiation is uncertain, it is expected to be very short, and in fact the final increase in emission rate of photons is expected to double in as little as 4000 years. The initial onset of Lyα will lead to an R-type ionization front, moving at a speed of the order of 10^4 km s^{-1} or more, which later develops into the much slower subsonic D-type front. If the stars are turning on their Lyα comparatively slowly, and we set the expansion speed at the sound speed in the undisturbed neutral gas, namely 1.4 km s^{-1}, the age is the time taken to expand to a radius of 500 AU, or 1700 yr. However, the rate of expansion will depend on the gas density in the neighborhood of the H II regions. Our previous analysis shows H II electron densities of 3.3×10^4 cm^{-3}, but estimates give an H_2 density of about 10^4 cm^{-3} based on CO (Sargent 1979) and NH_3 observations (Ho, Moran, and Rodriguez 1982). The latter values are obtained with beamwidths of $\geq$1'.4, so that over dimensions of a few arcsec, close to the newly formed stars, densities are likely to be greater. If we assume the thermal expansion mechanism by Spitzer (1978) and assume that the background density could be as high as $\sim 10^8$ cm^{-3}, the age is about 4000 yr, again assuming constant emission of Lyα photons. We note, however, that if the H II regions exist in a cavity of ionized gas where the density is less, as in the model by Ho, Moran, and Rodriguez (1982), the expansion speeds could be orders of magnitude greater.

However, the expansion of the H II regions is probably not governed solely by thermal pressure. The H II regions appear to exist in lines and, from their quasi-elliptical shape, to be expanding along the direction of the lines. If the lines were due to shock fronts, we would not expect to see the observed preferential expansion tangential to the shock. In fact observations of the H II regions produced by a star forming at a shock front show that preferential expansion, if any, is normal to the front (Hughes and Viner 1982).

One way of confining the H II regions would be by the presence of a magnetic field. If the field lines were along the line of H II regions, they would contain expansion normal to them, but allow expansion along them at the Alfvén speed. We can obtain an estimate of the magnitude of such a field by considering the flux amplification during the collapse of a cloud. It is normally assumed that the magnetic field, B, varies as $B \propto \rho^k$, where $\kappa = \frac{2}{3}$ for spherical collapse, but in general $\frac{1}{3} \leq \kappa \leq \frac{1}{2}$ if the collapse is preferentially down the field lines (Mouschovias 1979; Scott and Black 1980). If we take the mean density of H_2 in the cloud to be 10^4 cm^{-3}, and assume that the cloud has collapsed from an interstellar density of 1 cm^{-3} and a magnetic field of 3 microgauss, the mean value for B would be 1.4 milligauss if $\kappa = \frac{2}{3}$, or 0.3 milligauss if $\kappa = \frac{1}{2}$. The observations of Cep A by Wouterloot, Habing, and Herman (1980) suggest that these values are of the right order. An overall magnetic field of 1 milligauss could easily contain the thermal pressure of the H II regions, since $B^2/(8\pi) > nkT$, for values of n as high as 10^5 cm^{-3} and temperatures of 10^4 K. If the regions are expanding along the field lines at the Alfvén speed, $B(4\pi\rho)^{-1/2}$, then for an H_2 density of 10^4 cm^{-3} and $B = 1$ milligauss, the Alfvén speed is 15 km s^{-1}. An expansion to a radius of 2″ along the field lines takes 400 yr. It is not known if the magnetic field has increased much beyond a few milligauss, but in any case, if $\kappa = \frac{1}{2}$ the Alfvén speed will remain constant. Thus, the presence of a magnetic field could help account for the observations, but it is difficult to increase the age of the region to much beyond 10^3 yr, the age suggested by assuming expansion at the sound speed in the medium.

V. DISCUSSION

The observations have shown the presence of a cluster of about 14 compact H II regions which contribute to the total radio emission from the eastern source of Cep A. Of interest is the fact that these compact regions were not all observed by Rodriguez *et al.* (1980) who used only 10 elements of the VLA in comparison with our 26, though both sets of observations had the same resolution of ~1″. This can be explained when we compare the contour levels of Figure 2 with the flux determined by fitting elliptical Gaussian models to each source. Apart from sources 2 and 3, the maximum contour levels are about 0.3–0.6 mJy per beam, while the Gaussian fits give typical flux densities of 3 mJy. In the map by Rodriguez *et al.* (1980), which has contour intervals of 0.38 mJy per beam, there is evidence for some of the sources, but they are confused by the presence of noise at this level. Clearly the angular resolution used by Rodriguez *et al.* was such that most of the sources were resolved, with a resulting drop in flux density per beam area to about the noise level.

Recently, Lenzen and Hefele (1982) made extensive near-infrared observations with a 12″ beam of the area observed by us with the VLA. They find a number of sources. The central region shows some structure at low intensity levels, which resemble the structure of the radio map. However, the peak of the infrared emission is situated 15″ NNW of the sources 2 and 3 and does not coincide with any of the other sources. This can suggest that the area contains some other pre–main-sequence objects, not yet capable of ionizing the surrounding medium. It confirms a suggestion by Bally and Lane (1982) that the infrared peak is displaced from the radio peak. Mapping of the area in the infrared with a ≤5″ beam could produce interesting results.

We have suggested that the reason for the formation and elongation of the H II regions along a line could be the result of the presence of a magnetic field. However, there have been models computed which ignore the magnetic field and consider purely rotation. Such models have been reviewed by Bodenheimer (1981), who shows that if a cloud of gas is set in rotation and undergoes gravitational collapse, then a disk forms which then produces two condensations along a diameter in the disk. The computations start with a 5 $M_\odot$ cloud, and the condensations are each of 1 $M_\odot$, or about a Jeans mass. It is claimed that such calculations can be scaled to larger clouds, but with the greater mass, the small perturbations necessary to initiate the collapse could appreciably affect the fragmentation process. Thus it is difficult to see how this process would extrapolate to our case, where the total mass of Cep A is estimated by Sargent (1977) at 500 $M_\odot$.

Since the CO and NH_3 contours of Cep A show an elongation typical of that for an ellipsoid (Sargent 1977; Ho, Moran, and Rodriguez 1982), rotation about the minor axis of the ellipsoid might also be a convenient mechanism for explaining the bipolar emission that is observed. However, a close examination of the individual profiles in the region show that though the ^{12}CO profiles show many features, they are probably due to variations in optical depth across the region; the ^{13}CO profiles which have a much smaller optical depth show much less structure, and the maximum shift in the peak velocity along the major axis of the ellipsoidal cloud is ~1 km s^{-1}. This is over a distance of 7′ corresponding to ~3 beamwidths, or a linear distance of 1.5 pc, and does not indicate much rotation. In any case, since the width of the ^{13}CO profiles appear greater along the minor axis of the cloud, we would suggest that any rotation would be about the *major* axis, so that the lines of H II regions would be expected in a direction at right angles of that observed. However, the linear scales of the H II regions and the molecular cloud are different by a factor of >100, so that comparisons are difficult.

Computations on the collapse of a cloud with associated magnetic field have been discussed by Mouschovias (1981), where again it is suggested that in the process of collapse a ring will form centered on the axis of rotation. However, this depends on the assumed ambipolar diffusion timescale in the gas, which Scott (1983) shows to be in error. More detailed models for rotating clouds containing a magnetic field have been carried out by Dorfi (1982). They show that if the magnetic axis is either parallel or normal to the axis of rotation, the cloud will collapse to form a slab, with various inflows and outflows. However, the model deals only with the initial stages of collapse, down to densities of 10^4 cm^{-3}, where it is expected that ambipolar diffusion will occur. In either case, none of the models predict the formation of stars in lines as is observed.

In the case of Cep A we suggest that collapse of the cloud has led to a prolate spheroid with the magnetic field aligned along the axis. The value for the magnetic field is estimated at a few milligauss, and it is of interest that a field of 3.5 milligauss was inferred by Wouterloot, Habing, and Herman (1980) from the Zeeman splitting of the OH maser line. Such a field could contain an H II region of density $\sim 10^6$ cm^{-3} expanding at a velocity of 5 km s^{-1}. It was further inferred that a magnetic field was producing large Faraday rotation in the region. Such a model is at variance with that suggested by Königl (1982) where bipolar flows are the result of the control of an expanding bubble by a magnetic field. This would mean that the magnetic field would be directed approximately at right angles to that proposed as causing the lines of H II regions. As suggested, small-scale fields may not necessarily be oriented in the same direction as larger scale fields. Clearly, further high-resolution line observations are needed so that the presence of a magnetic field can be confirmed; but also necessary are high-resolution observations in the region of the bipolar flow.

A magnetic field could play also a further role in the area. It has been pointed out that the mass motions of up to ± 25 km s^{-1} (Rodriguez *et al.* 1980; Ho, Moran, and Rodriguez 1982), as shown by wings in the CO line, and their large angular extent, rules out the possibility of the associated gas being gravitationally bound to the gas of the Cep A condensation, and leads to the suggestion of the expansion of the gas in bipolar flows. On the other hand, the presence of an overall magnetic field of 1 milligauss parallel to the galactic plane, could contain this motion. The wide angular extent of the flow, covering a region of dimension at least 1'.5, and the small angular extent of the H II regions, suggests that the flow may be more a property of the cloud itself, rather than being controled by the star-forming regions. Such a suggestion is at variance with that normally proposed for bipolar flows, but there is no reason why it should not explain the situation in Cep A. The period of rotation of the gas undergoing this rotation is estimated to be 3×10^4 yr, which is much greater than the estimated age of 10^3 yr for the H II regions. In addition, we have noted that the CO contours of the Cep A condensation are elongated roughly along the same direction as the H II regions, and that Cep A appears to be a quasi-ellipsoidal cloud of gas undergoing some rotation about the axis of the prolate. Rotation of the cloud would cause some of the magnetic field lines in the area to become twisted into helices, so that star formation in Cep A could have occurred near to the center of the cloud, on a line along the axis, and, in addition, on one of these twisted helical field lines.

A further point of considerable interest is the fact that the contours of the red- and blueshifted components of the line, as shown in Figure 1, extend over a large angle; the redshifted line in fact encompasses the radio source 1 which is associated with optical emission. If source 1 and the other sources are associated, and their closeness would suggest that they might be, then it would appear that the optical nebulosity, which must be on the near side of the cloud, is associated with some source which is driving gas away from us into the molecular cloud, along the line of sight, or the cloud boundary is somewhat further from us at the position of the source. The alternative is that the nebulosity is produced in some way by infall onto the cloud.

As a final point, it is noted that all stars appear to be of the same spectral type, which is probably as expected since the physical conditions for forming each star are similar, considering their small spatial separation. Normally, when stars have dispersed their surrounding gas and they make their visual appearance, they exhibit a mass spectrum. The close transverse separation of the stars in Cep A, being in some cases as small as 1000 AU, suggests that not only will binaries form, but there is the distinct possibility that some stars will coalesce to form more massive stars (with the release of energy in the form of outflow) and that this may later result in the observed mass spectrum. On the other hand, our estimated age since the "turning-on" of the B3 stars is quite short in comparison with the other time scales normally associated with the earlier stages of star formation. It appears that star formation could have been triggered by, for instance, the molecular cloud encountering the shock front associated with the galactic spiral pattern. In this case, if we assume an initial cloud density of $\sim 10^4$ AMU cm^{-3}, the free-fall time would be $\sim 10^5$ yr, about equal to the Kelvin-Helmholtz time scale, and ~ 100 times greater than our estimated age for the H II regions. The final stages of collapse could have been faster, but we suspect that there could be further pre–main-sequence objects in the region with insufficient ionizing radiation to produce H II regions, as we have suggested from the infrared results of Lenzen and Hefele (1982). Such suggestions may be somewhat speculative, but may well be worth considering if the conditions in Cep A are at all representative of star-forming regions.

VI. CONCLUSIONS

This paper has described results which show that in the Cep A molecular cloud there exists two strings of H II regions, each about 0.1 pc long. There is a total of 14 regions, and each can be attributed to a B3 star, provided that the stars are equivalent to main-sequence stars. The fact that the stars have formed in lines is used as evidence that in this case a magnetic field controls star formation. Of particular interest is the very young age of the stars, about 1000 yr, and the fact that they are close together, separated in some cases by as little as 1000 AU. This suggests that binary stars will be produced, and that some stars may coalesce to form more massive stars. Also, the estimated very young age of the H II regions suggests that other stars may be forming in the region with as yet only small amounts of energy output. If we are correct, then these results may influence greatly ideas on the initial stages of stellar evolution.

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V. A. HUGHES: Astronomy Group, Department of Physics, Queen's University, Kingston, ON K7L 3N6 Canada

J. G. A. WOUTERLOOT: European Southern Observatory, Karl-Schwarzschild Strasse 2, D-8046 Garching bei München, West Germany