

## THE STRUCTURE OF THE INNER R AQUARI NEBULA IN THE LIGHT OF $H\alpha$ AND $[N II]$ $\lambda 6584$ EMISSION<sup>1</sup>

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### ABSTRACT

We used the Space Telescope Science Institute (STScI) coronagraph on the ESO 2.2 m telescope in conjunction with narrow-band interference filters to image the immediate surroundings of the symbiotic variable R Aquarii in the light of the bright nebular emission lines of  $H\alpha$ , 6563 Å and  $[N II]$ , 6584 Å. Most of the contaminating radiation from the very bright core ( $m_v = 9.0 \pm 0.3$  at the time of observation) is suppressed by a 1".24 thick occulting wedge allowing a relatively unrestricted view of the surrounding region out to  $\sim 15''$  at sub-arcsecond spatial resolution. We easily detect all the previously established features of the inner nebula including the faint southern loop and knot at 8", 200° p.a., the bright knots at 2".5, 45° p.a., and 6".5, 30° p.a. In addition, however, we detect a new, bright, unresolved feature prominent in both  $H\alpha$  and  $[N II]$  emission at 8".4 from the nucleus at 20° p.a., emitting a total flux of 1.7 and  $2.2 \times 10^{-12}$  ergs cm<sup>-2</sup> s<sup>-1</sup> in the  $H\alpha$  and  $[N II]$  lines, respectively, and, possibly, a weaker one visible only in  $H\alpha$  at 3".8, 306° p.a. Both the  $[N II]/H\alpha$  ratios of  $\sim 1.2$ – $1.8$  measured in the previously identified features and their positions are consistent with those obtained by Solf and Ulrich in 1982–1983, indicating that they have not evolved significantly in the last few years. The new feature at 20° p.a. has a  $[N II]/H\alpha$  ratio of 1.3 strongly suggestive of shock-wave heating or photoionization by a power-law continuum as the principal excitation mechanisms. The small radial velocity and proper motion of the features and the probable formation of a new one at the end of the jet also suggests that they are excited by an outwardly propagating disturbance.

*Subject headings:* nebulae: individual (R Aqr) — stars: individual (R Aqr) — stars: symbiotic

### 1. INTRODUCTION

R Aquarii is a D-type symbiotic variable exhibiting a wide variety of peculiar characteristics (Kenyon 1986; Michalitsianos 1984). The bright, optically unresolved central object consisting of a cool Mira variable and a hot unseen ionizing source of radiation is surrounded by a morphologically complex, time-variable emission nebula (Sopka *et al.* 1982). Three distinct optical emitting regions composing this nebular structure can be identified presently (Solf and Ulrich 1985). The first is an outer formation of  $\sim 2'$  diameter extending mainly along the E-W axis and expanding at a rate of  $\sim 50$ – $100$  km s<sup>-1</sup>. The second is an inner structure of  $\sim 1'$  extent spread out mainly along the N-S axis and merging smoothly in most low-resolution images with the bright, compact central source. Most of the emitting plasma in this inner nebula also expands at approximately the same rate as the outer nebula. These two structures seem to be relatively stable geometrically since their discovery (Lampland 1923), although some features in the inner nebula may have faded slightly in the last few years (Sopka *et al.* 1982).

Approximately a decade or so ago, a third structure was identified within the inner nebula that did not appear in previous investigations. This consisted of a spike of emission resembling a jet oriented along the N-E axis, extending out to  $\sim 7''$  from the nucleus and  $\sim 10$  times as bright as the surrounding features of the inner nebula (Sopka *et al.* 1982). The brilliant spike itself has been resolved at optical and radio wavelengths into two distinct features outside the nucleus

(Hollis *et al.* 1985; Maunon *et al.* 1985) that seem to be roughly aligned with a third compact radio feature recently identified at 2 cm within the nucleus at a distance of  $\sim 0.5'$  from the center of the brightest radio emission clump (Hollis *et al.* 1986). The position of the long-period Mira variable is offset a few tenths of an arcsecond with respect to the brighter radio feature C1 in the compact optical core (Michalitsianos *et al.* 1988). From wide-field, narrow-band optical images centered on the  $[O III]$  5007 Å line, there is evidence for an extended S pattern oriented N-S in the nebula that can be followed out to more than an arcminute from the nucleus and reminiscent of the effects of a precessing disk or rotating source geometry (Michalitsianos *et al.* 1988). The nucleus and the brighter parts of the nebula have been observed in the UV with *IUE* (Kafatos, Michalitsianos, and Hollis, 1986, and references therein), and the entire system has also been unambiguously detected in soft X-rays with *EXOSAT* (Viotti *et al.* 1987), albeit at low fluxes.

On the basis of a detailed high spectral and spatial resolution investigation of the optical nebula around R Aqr, Solf and Ulrich (1985), amplifying a suggestion first made by Hubble (1943) and Baade (1943, 1944), have proposed that the whole structure can be best understood in terms of two major, successive explosions or outbursts occurring in the nucleus approximately 640 and 185 yr ago. The observed geometry and kinematics of the outer and most of the inner nebula fits remarkably well the expected effects of such explosions provided the expansion of the material occurs at rates that are minimum in an equatorial plane seen almost edge-on to our line of sight and increasing with increasing latitude angle of the flow. This is what might be expected if the explosion occurred within a flat disk wherein a high concentration of material impedes the expansion of the shock front in the disk

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plane but much less so in a direction perpendicular to it resulting in the observed bipolar flow pattern. This disk is most plausibly related to the binary nature of the central source of the R Aqr system for which there is considerable, although not definitive, evidence (Kafatos *et al.*). In this possible scenario, the equatorial plane of the observed shells of emission would coincide with the orbital planes of the system and the explosions due to increased activity in an accretion disk surrounding the hot companion.

The one major discrepancy with this model is the puzzling kinematical and optical behavior of the bright extended spike of the jet in the NE with peak surface brightness located at 6".5 from the nucleus at 30° p.a. The origin of this particular feature and its, apparently, related unresolved one at 2".5, 45° p.a. is the subject of intense controversy at present. Three different and contrasting explanations have been recently put forth for its appearance and evolution. First, Solf and Ulrich (1985) espouse the theory that all the features in the jet are intimately connected to and coeval with the explosive event that produced the inner nebula. In this view, the discrepant feature at the end of the jet is the manifestation of an obstruction in the flow of the expanding inner shell due to a dense clump of gas or dust left over from the previous explosion. The obstruction forces the gas in the shell to decelerate rapidly and to form a shock that excites the clump of material to radiate. Its recent appearance is due simply to the recent deceleration event for which there is some supporting kinematic evidence. This model does not adequately explain the apparently ordered geometry of the ejecta, however.

A second explanation has been suggested by Spergel, Giuliani, and Knapp (1983) who speculate that all the bright features in the jet are actually stationary condensations of gas in the extended wind of the Mira that are normally shielded from the hot ionizing source by the Mira itself and/or by dust clouds nearby. As the ionizing source moves in its orbit around the Mira, however, it eventually reaches a point from which it can directly illuminate the condensations. At this time they will appear to brighten considerably, as observed.

A third possibility proposed by Kafatos *et al.* is that the bright features are actually part of a moving collimated jet of material expelled more recently in successive episodes from the outer edge of a thick accretion disk around the hot companion of the Mira. These episodes are linked to the relatively sudden heating of the disk at periastron passage when matter is rapidly transferred from the Mira to the compact, hot companion. During these times, matter is expelled at the relatively low velocities observed ( $\leq 100 \text{ km s}^{-1}$ ) from the outer edge and an intense flux of ionizing radiation contained in two oppositely directed cones of opening angle 150° is emitted from the much hotter inner edge of the accretion disk. This explains both the sudden appearance of the jet only a decade ago and the present position of the optical and radio features provided one assumes the binary's periastron passage occurs approximately every 50 yr or so with one having occurred recently. The last assumptions do have some supporting evidence from observations of the variable's light curve and some peculiarities associated with its spectrum in the 1930s (Kafatos, Michalitsianos, and Hollis 1986).

The recent observation of a distinct S-shaped N-S oriented and symmetric bipolar flow pattern in the [O II] 5007 Å nebular emission (Michalitsianos *et al.* 1988) that seems to follow the trajectory described by the jet features in the NE portion of the inner nebula is suggestive of the effect of a

quasi-continuous expulsion of matter from a rotating central source over a considerable period of time. The curious absence of a prominent counter jet feature in the SW portion of the inner nebula could be ascribed, in this scenario, to the action of a precessing accretion disk interacting with the extended long-period variable (LPV) envelope or to episodes of enhanced mass loss in the LPV.

Unfortunately, none of the hypotheses just described seems to be able to explain all the observed characteristics completely satisfactorily, in fact, and some combination of the three or a completely new one might be required to do the job. In view of the overriding importance of better understanding its extraordinary behavior, and applying this knowledge to a whole class of active objects emitting matter and radiation from the X-rays to the microwave, we decided to take a more detailed look at R Aquarii with a high-precision coronagraph. This technique allows us to study in unprecedented detail the close surroundings of the bright central nucleus with a minimum of contamination from scattered light in the instrument and the object's seeing disk even when the object is at maximum light.

In this paper, we present the first results of our investigations into the structure of the inner R Aqr nebulosity in the emission lines of H $\alpha$  and [N II], 6584 Å at high spatial resolution in the form of photometrically accurate contour maps of the region. We show that in the inner 15" and beyond the arcsecond diameter core, several line-emitting features stand out from the sky background presently. Three features were previously observed in approximately the same positions including the faint southern loop with knot and jet features at 2".5 and 6".5 in the NE quadrant. We report the appearance, however, of a bright new feature at 8".4 from the nucleus, very prominent in both emission lines, probably associated with the extended feature at the end of the jet. We estimate from results in the published literature that it appeared sometime between 1984 January 20 and 1986 November 28, the date of our observation. The recent appearance of this feature and its physical characteristics place severe constraints on theoretical models of the emission region.

## II. OBSERVATIONS AND DATA REDUCTION

The data presented here were obtained on 1986 November 28 at the 2.2 m Max-Planck-Institute (MPI) Cassegrain telescope at the European Southern Observatory, La Silla, Chile. The optical configuration of the observational setup at La Silla is described in detail in Paresce and Burrows (1987a, b) and Burrows, Paresce, and Evzerov (1988) and is shown schematically in Figure 1. Briefly, light from the central source is focused onto a blackened photoetched mask located in the telescope focal plane. This occulting mask is shaped in the form of a long thin wedge which can be moved longitudinally by a micrometer in order to vary its projected width in the sky from 1" to 10" depending on seeing conditions and source brightness. It can also be moved transversely to occult any desired portion of the field of view. Following the mask, an achromatic doublet reimages the telescope focal plane with a magnification of 5 onto the detector so that the effective focal ratio of the system becomes f/40.

An apodizing mask especially designed to reduce diffracted stellar light from the 2.2 m telescope pupil is located in the exit pupil and is rigidly attached to the lens mount to ensure that it remains there as the coronagraph is focused. The mask obscures ~30% of the exit pupil close to the images of the

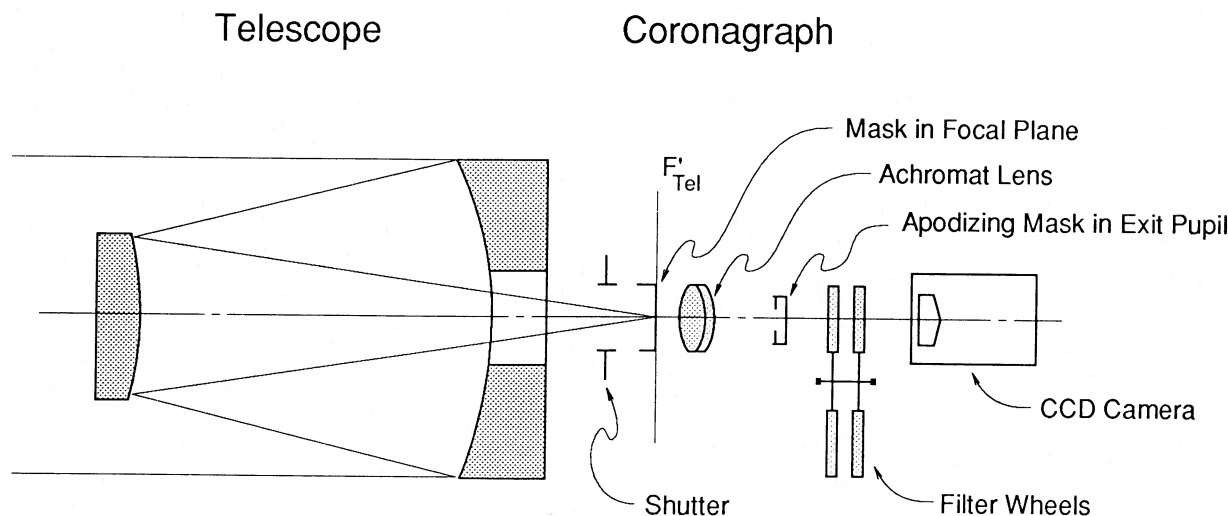


FIG. 1.—Schematic of the optical configuration of the observational arrangement at La Silla

entrance pupil edges. After this mask, the light passes through optical filters in a rotating commandable two-wheel assembly mounted just in front of the detector which is a  $512 \times 320$  30 micron square pixel RCA backside-illuminated CCD. In this particular configuration, each pixel corresponds to  $5 \times 10^{-3}$  square arcseconds in the sky with a total rectangular field of view of  $22''.5$  by  $35''.9$ .

Two narrow-band interference filters and a broad bandpass  $R$  filter were used in this study. One interference filter was designed to isolate the  $H\alpha$  line with a peak transmission of 0.51 at  $6562.3 \text{ \AA}$  and a FWHM of  $12.3 \text{ \AA}$  while the other was designed to isolate the  $[N II]$   $6583 \text{ \AA}$  line with a peak transmission of 0.53 at  $6586.6 \text{ \AA}$  and a FWHM of  $19 \text{ \AA}$ . The  $R$  filter was used for the continuum subtraction and exhibited a peak transmission of 0.86 at  $6000 \text{ \AA}$  and a FWHM of  $1565 \text{ \AA}$ . The complete system was calibrated absolutely using standard stellar calibration sources observed through the  $R$  filter. The resultant overall counting efficiencies were 21% for the  $R$  bandpass at  $6570 \text{ \AA}$ , 15% for the  $H\alpha$  filter at  $6562.3 \text{ \AA}$ , and 16% for the  $[N II]$  filter at  $6586.6 \text{ \AA}$ . In the  $R$  band the sensitivity of our system amounted to  $\sim 3340$  detected photons per second for a 1 mJy source ( $10^{-26} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}$ ). Through the interference filters, the sensitivity in the same units is 20.2 and 11.3 for the  $H\alpha$  and  $[N II]$  filters, respectively.

$R$  Aquarii is first placed on the unocculted area of the field with the  $R$  and neutral density (ND) filter in the beam, and the resultant image is used to focus the telescope secondary. During our observations, the FWHM of the seeing disk in focus amounted to  $0''.9$ . The total count rate from the source corresponded to a flux density of  $1.1 \times 10^4$  mJy in our  $R$  passband. From this and an assumed M7 III spectrum we estimate that the Mira LPV was  $m_v = 8.6$ , consistent with  $m_v = 9 \pm 0.3$  object as estimated by Mattei (1987) for the date of the measurement.

Using the telescope TV autoguiding system,  $R$  Aqr is placed behind the occulting wedge in a series of short acquisition exposures. With a series of increasingly smaller offsets, the source is centered behind the occulting wedge. This is accomplished by making the spillover light distribution above and below the wedge obtained with progressively less ND attenuation as symmetrical as possible. Finally, any ND filter remaining is removed and the long exposure in the specified bandpass

begun. We estimate the centering accuracy thus obtained to be of the order of a few tenths of an arcsecond. The telescope pointing stability is also of order  $\pm 0''.1$ , normally, although sudden shifts of much greater magnitude have been observed to occur very infrequently, but they are usually obvious enough that they can be corrected for.

Three exposures of this type were obtained on the night of 1986 November 28 through the filters described above. The first, of 20 minutes duration, was carried out with the  $N II$  filter, the second, of 30 minutes duration, with the  $H\alpha$  filter, and the last, of 0.5 minute duration, with the  $R$  filter. The raw images were processed in a standard way to prepare them for scientific analysis. The effects of CCD bias level and the variations in response across the detector area are removed by subtracting a bias level derived from an overscan region and by dividing by a flat field taken through the  $R$  filter a few hours before. Obvious cosmic-ray blemishes and local CCD defects are located and patched up by linear interpolation between neighboring pixels. The sky background level was determined from the corners of the field and subtracted from each image.

The results of this processing are shown in Figure 2 (Plate 9), top row. On this row, the image on the left corresponds to the 0.5 minute exposure with the  $R$  filter, the one in the center the 30 minute exposure with the  $H\alpha$  filter, and the one on the right the 20 minute exposure with the  $[N II]$  filter. The occulting wedge is  $1''.24$  wide in all images presented here. North is up, east to the left, and the contours occur at equal intensity intervals. The faint southern loop and knot are visible in the images presented in Figure 2. The diffuse patch of  $N II$  emission in the NW is an instrumental artifact. Assuming  $R$  Aqr is at 200 pc,  $1''$  in these images corresponds to a linear scale at the source of  $3 \times 10^{15} \text{ cm}$  or 200 AU and a light travel time of just over a day.

### III. ANALYSIS

The signal in the central part of the broad-band  $R$  image shown in the left panel of Figure 2, top row, is due primarily to scattered light from the Mira LPV that is incompletely suppressed by the coronagraph. We have used the apparent center of the spillover light distribution in this band to bring all the images into spatial registration. Small image shifts between or

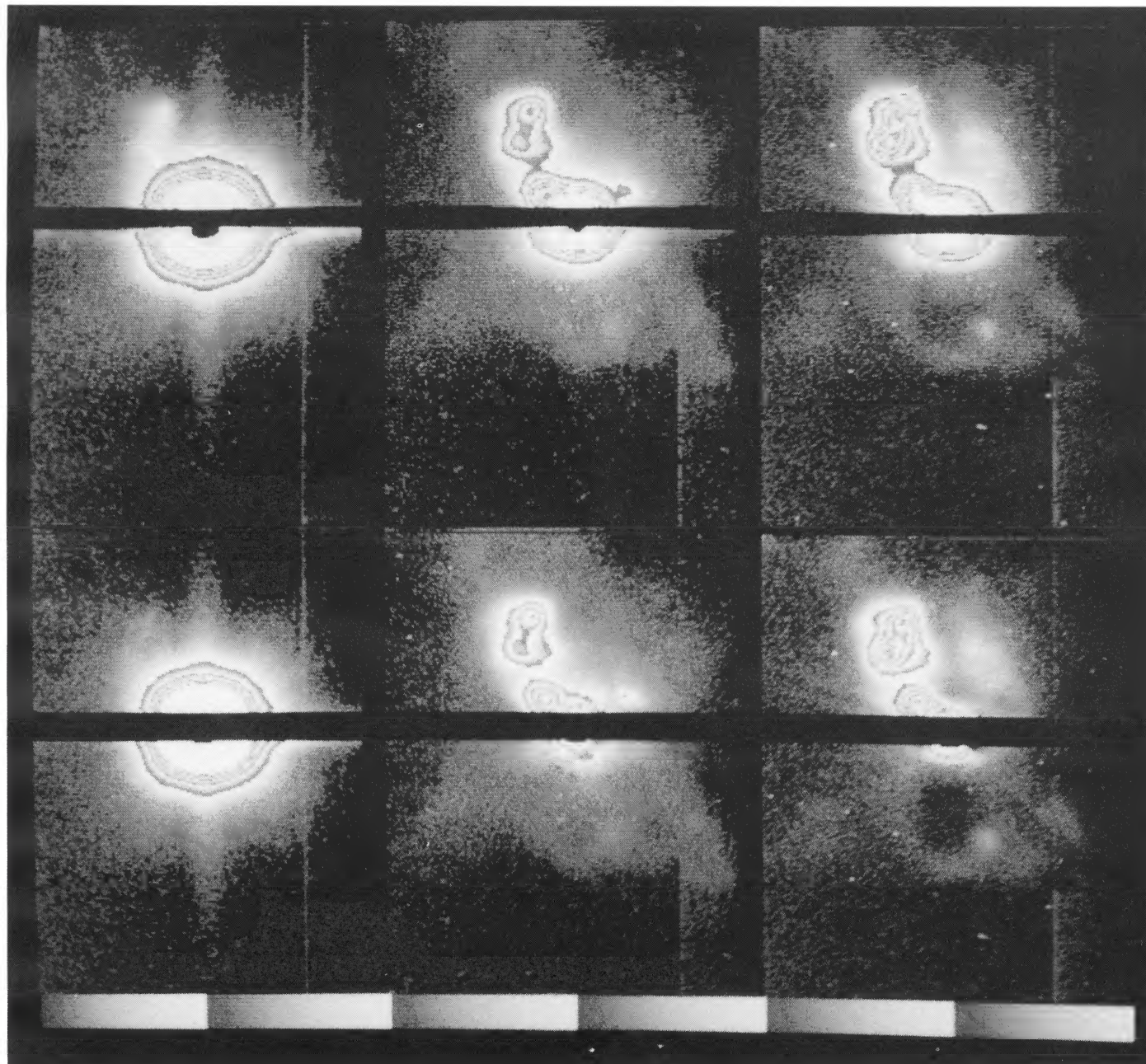


FIG. 2.—*Top row:* Initial CCD images of R Aqr in a broad-band  $R$  filter (*left*) and in narrow-band filters centered near  $H\alpha$  (*center*) and  $[N\ II]\ \lambda 6584$  (*right*). *Bottom row:* Final images in which the emission-line contributions are subtracted from the  $R$  image, and the glow from the Mira LPV, which is located behind a horizontal occulting bar, is subtracted from the  $H\alpha$  and  $[N\ II]$  images. North is up and E to the left. The R Aqr “jet” extending NE from the Mira LPV consists of knots A at  $2''.8$ , B at  $7''.0$ , and the new knot D at  $8''.4$ . Weak emission extending beyond these knots, and southern features including knot S and associated loops, are confirmed from previous investigations. The diffuse  $[N\ II]$  patch and  $H\alpha$  knot in the NW quadrant are probably instrumental artifacts. Cosmic-ray hits and a bad CCD column are also evident.

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during exposures cannot be ruled out because once the centering procedure described in § II was accomplished with the first acquisition frames, no further readjustment was attempted during the series of exposures that followed. Thus, we found that the H $\alpha$  image had to be shifted one pixel west and one pixel south, while the [N II] image had to be shifted the more substantial amount of two pixels west and seven pixels south in order to bring them into registration with the center of the R image. We estimate the accuracy of this procedure to be of order  $\pm 0''.15$  due to the uncertainty in the location of the real center of the contours hidden behind the occulting wedge. With this shift, the prominent emission features to the NE were also brought into registration with the same uncertainty.

After applying these shifts, the scattered light from the LPV determined from the R band image can be largely eliminated from the narrow-band images by subtracting a fraction of the broad-band image. The narrow H $\alpha$  and [N II] passbands do not completely isolate their respective line emission features; about 5% of the signal is produced by lines on the wings of the passbands. We corrected for these cross talk effects by using synthetic photometry techniques to compute the expected contribution of the Mira and emission-line spectra in the three passbands. For each detector pixel, let  $F_R$  be the flux density of the stellar component,  $J_{H\alpha}$  the flux of the H $\alpha$  emission line, and  $J_{NII}$  the flux of the N II lines at  $\lambda 6548$  and  $\lambda 6583$ . The spectrum of the light falling on each detector pixel is then

$$f_\lambda(\lambda) = F_R S_\lambda(\lambda) + J_{H\alpha} \delta(\lambda - 6562.5) + J_{NII} \frac{1}{4} \delta(\lambda - 6548.1) + \frac{3}{4} \delta(\lambda - 6583.4) .$$

Here  $S_\lambda(\lambda)$  represents the spectral shape of the scattered light from the Mira variable, for which we take the (suitably normalized) spectrum of SW Virginis (M7 III) from the Gunn-Stryker (1983) atlas. The Dirac delta function  $\delta(\lambda)$  is used to approximate the narrow profiles of the emission lines. The number of detected photons in passband  $P(\lambda)$  is then given by

$$N(P) = At(P) \int P(\lambda) \frac{f_\lambda(\lambda)}{h\nu} d\lambda ,$$

where  $A = \pi(110 \text{ cm})^2$  is the area of the telescope, and  $t(P)$  is the exposure time in seconds.

From the observed count rates in the three passbands,  $N(R)$ ,  $N(H\alpha)$ , and  $N(N II)$ , we have three linear equations from which

to solve for the stellar flux density  $F_R$  and the emission-line fluxes  $J_{H\alpha}$  and  $J_{NII}$ :

$$\begin{aligned} F_R &= 0.02770N(R) - 0.00057N(H\alpha) - 0.00141N(N II) \\ J_{H\alpha} &= -0.00158N(R) + 0.00845N(H\alpha) - 0.00053N(N II) \\ J_{NII} &= -0.00425N(R) - 0.00181N(H\alpha) + 0.01853N(N II) \end{aligned}$$

In these equations,  $F_R$  is in units of mJy arcsec $^{-2}$  while  $J_{H\alpha}$  and  $J_{NII}$  are expressed in units of  $10^{-13}$  ergs cm $^{-2}$  s $^{-1}$  arcsec $^{-2}$ . The clean continuum and emission-line pictures shown in the bottom row of Figure 2 are formed by taking the appropriate linear combinations of the three observed images. The jet features visible in the raw broad-band image are evidently due to the contribution of the emission lines to the R passband, since the jet is not apparent in the clean continuum picture. However, the synthetic photometry results given above did not subtract an optimum fraction of the continuum from the emission-line pictures, leaving a residual image of the Mira glow. We therefore adjusted the appropriate matrix coefficients, from  $-0.00158$  to  $-0.00250$  and from  $-0.00425$  to  $-0.00170$ , to eliminate the Mira glow.

The contour images of the R Aquarii nebula in the light of the H $\alpha$  and [N II] emission lines obtained in this manner are shown in Figures 3 and 4, respectively. The orientation is the same as in Figure 2. The contour intensity levels are separated by factors of  $2^{1/2}$ . Four conspicuous features stand out clearly from the background in both these images. We measured the positions of these features by locating the pixel with the greatest surface brightness after convolving the images with a five pixel ( $0''.35$ ) boxcar filter. Integrated line fluxes were then determined for each feature by summing the signal from all pixels within appropriate rectangular or circular apertures centered on the measured positions. The fluxes of features B and D were somewhat arbitrarily divided by a horizontal line halfway between their positions. Our measurements of the positions and total line fluxes of these features relative to the nucleus of R Aqr for the epoch of observation (1986.91) are listed in Table 1. Also listed in this table for comparison are the positions of the previously established features of the inner nebula from recent radio 2 cm (Hollis *et al.* 1985), and U band (Mauron *et al.* 1985) observations.

Within the stated uncertainties, our first three features are clearly coincident with feature A and the peak of feature B and what we have called the southern knot S already identified in the previous investigations referenced. We see more extended

TABLE 1  
PROMINENT EMISSION-LINE FEATURES OF THE INNER R AQUARI NEBULA

| Feature | Epoch   | R                 | p.a.                   | $F(H\alpha)^a$ | $F(N II)^{a,b}$ | N II/H $\alpha$ | Reference |
|---------|---------|-------------------|------------------------|----------------|-----------------|-----------------|-----------|
| A ..... | 1982.74 | $2''.66 \pm 0.16$ | $45^\circ \pm 3^\circ$ | ...            | ...             | ...             | 1         |
|         | 1983.94 | $2.67 \pm 0.15$   | $47 \pm 3$             | ...            | ...             | ...             | 2         |
|         | 1986.91 | $2.79 \pm 0.15$   | $45 \pm 3$             | 24             | 29              | $1.2 \pm 0.1$   | 3         |
| B ..... | 1982.74 | $6.4 \pm 0.16$    | $29 \pm 2$             | ...            | ...             | ...             | 1         |
|         | 1983.94 | $6.51 \pm 0.15$   | $33 \pm 2$             | ...            | ...             | ...             | 2         |
|         | 1986.91 | $6.80 \pm 0.15$   | $32 \pm 2$             | 18             | 31              | $1.8 \pm 0.1$   | 3         |
| S ..... | 1983.94 | 7.7               | 204                    | ...            | ...             | ...             | 2         |
|         | 1986.91 | $7.68 \pm 0.15$   | $197.5 \pm 1.5$        | 0.6            | 0.8             | $1.5 \pm 0.3$   | 3         |
| D ..... | 1986.91 | $8.44 \pm 0.15$   | $20 \pm 1$             | 17             | 22              | $1.3 \pm 0.1$   | 3         |

<sup>a</sup> Units:  $10^{-13}$  ergs s $^{-1}$  cm $^{-2}$ .

<sup>b</sup> The [N II] line flux includes both 6583 and 6548 Å with an assumed ratio of 3 ÷ 1.

REFERENCES.—(1) Hollis *et al.* 1986; (2) Mauron *et al.* 1985; (3) This work.

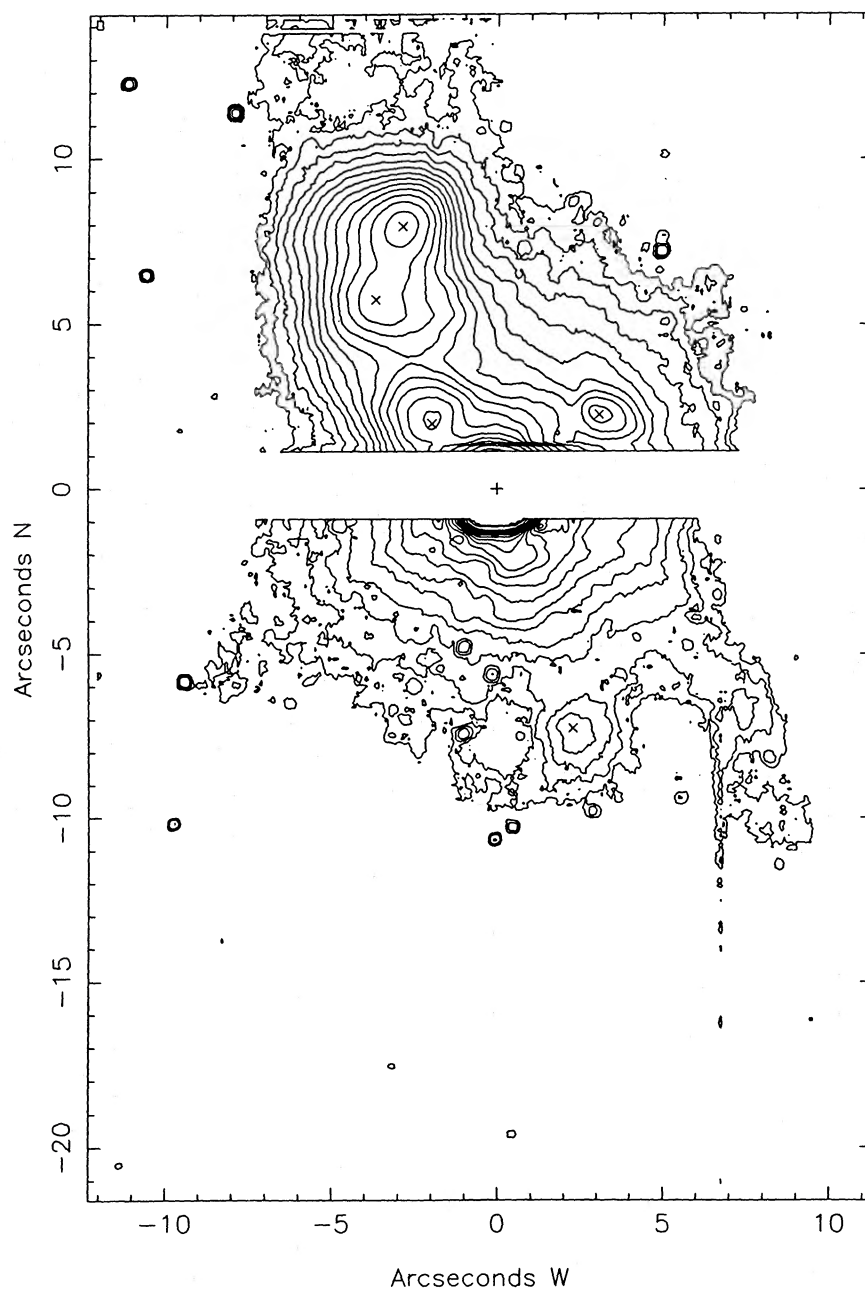


FIG. 3.—Contour diagram showing the morphology of the H $\alpha$  (Fig. 3) and [N II] (Fig. 4) emission from the inner nebula of R Aqr. Contour levels are separated by factors of  $2^{1/2}$  and the lowest contour corresponds to an H $\alpha$  surface brightness of  $0.05 \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}$ . Scattered light from the Mira LPV, located behind the occulting wedge and marked by (+), has been subtracted. The measured positions of several bright emission knots are marked by x's. The seeing was  $0''.9$  FWHM. Cosmic-ray blemishes appear as  $0''.35$  features because the original CCD image was smoothed with a  $5 \times 5$  pixel boxcar filter. A bad CCD column affects the data at  $6''.8$  west.

structure around the knot S in the form of arches or loops (see Fig. 2) that are probably the faded remnants of the southern loop described by Solf and Ulrich (1985). There is no evidence from our data of a faint counterjet structure in the south in the H $\alpha$  and [N II] emission lines. If it is there, its surface brightness is at least 10 times fainter than that of knot A. The faint feature appearing only in the H $\alpha$  images located at  $3''.8$ ,  $306^\circ$  p.a., has not been seen before, but its existence needs to be confirmed with another observation. It appears at an H $\alpha$  flux of  $\sim 3 \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1}$ .

If we intercompare feature positions listed in Table 1 derived

from optical,  $U$ ,  $R$ , and radio measurements taking into account the various sources of error, we obtain a possible outward proper motion of feature B of  $0''.15 \pm 0''.05 \text{ year}^{-1}$ , a value consistent with the upper limit derived by Maun et al. (1985). Although the proper motion of knot B is formally significant, we prefer to regard the measurement as an upper limit because the total displacement over the time base of 10 yr is still less than the dimensions of the feature. Thus the apparent motion may reflect morphological changes in the knot rather than outward motion. At a distance of 200 parsecs this limit corresponds to a velocity of less than or equal to  $140 \text{ km s}^{-1}$ .

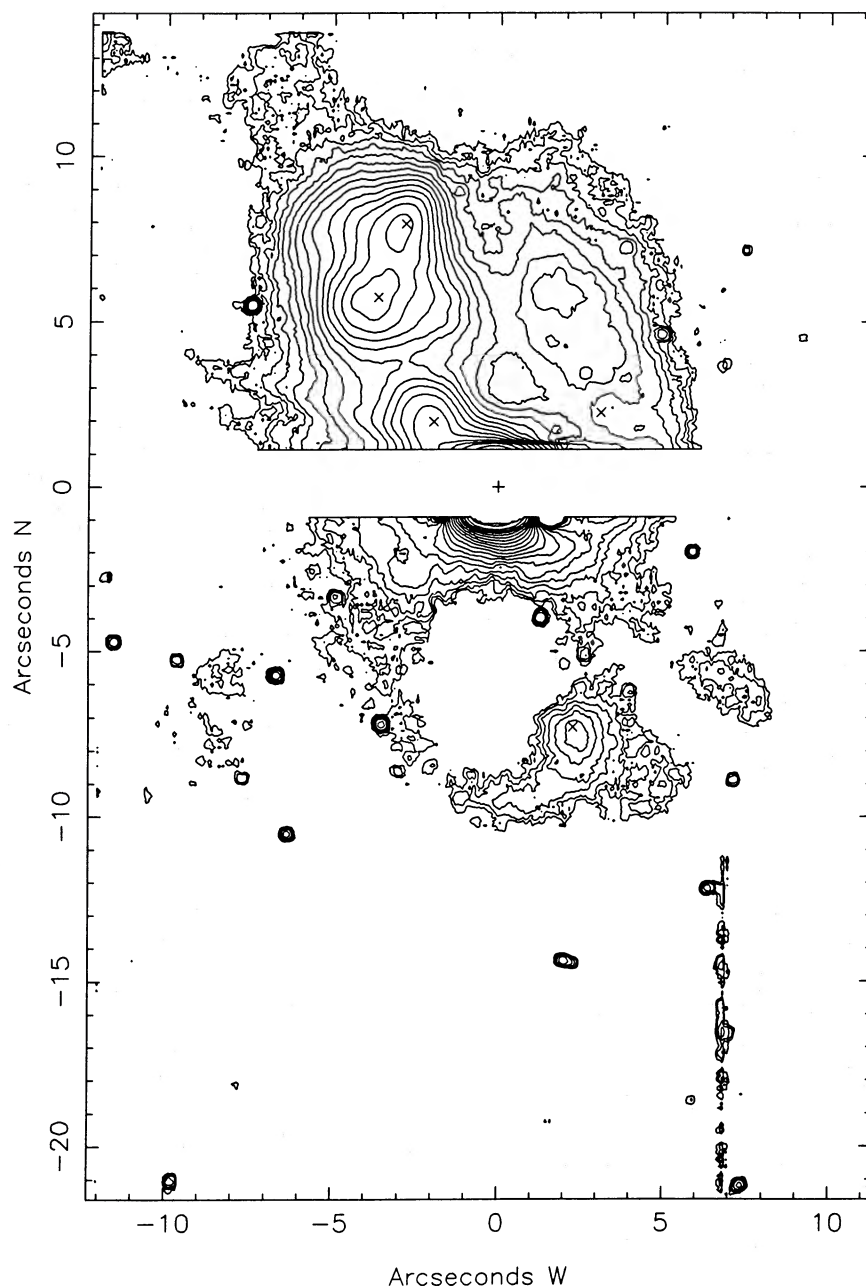


FIG. 4.—Same as Fig. 3 for [N II]

within a factor of 2 of the measured radial velocities in the area (Solf and Ulrich 1985).

Feature A is spatially unresolved in our data, while features B and D have a FWHM of  $2''.0$  compared with the seeing profile FWHM of  $0''.9$ . It is also clear from Figures 3 and 4 that B and D are asymmetric in the sense that feature B is more extended to the west, while the opposite is true for feature D. Similar asymmetric structure is present in the UV image of Mauron *et al.* (1985), except that the bright core of feature D was not then present.

The  $H\alpha$  line fluxes tabulated here for the main features of the inner nebula can be compared to the fluxes measured by Michalitsianos *et al.* (1988). The comparison is approximate since their resolution is insufficient to resolve individual fea-

tures in the jet and their data are significantly contaminated by scattered light from the core. Nevertheless, they find in the general area of features B and D an  $H\alpha$  line flux of  $\sim 2 \times 10^{-12}$  ergs  $\text{cm}^{-2} \text{s}^{-1}$  over an angular area of 4 arcseconds<sup>2</sup> compatible with their spatial resolution. This is in good general agreement with the fluxes we derive, and it indicates that the  $H\alpha$  flux from the inner nebula is reasonably constant (within a factor of 2–3 at least) over a time interval of several months.

Finally, the derived [N II]/ $H\alpha$  ratios in the range 1.2–1.8 for the features described in Table 1 are in excellent agreement with those observed spectroscopically by Solf and Ulrich (1985) in 1982/1983. This is a strong indication that the excitation mechanism responsible for the observed line emission has not changed significantly in the last 2–3 yr.

## IV. DISCUSSION

A review of the literature shows that most of the features we have observed to emit in the  $H\alpha$  and  $[N\ II]$  lines have probably been seen before under a variety of observing conditions and spectral bandpasses. Feature A is certainly the same one observed in the radio and optical (Hollis *et al.* 1985), UV (Mauron *et al.* 1985),  $V$  (Sol 1983),  $[N\ II]$  6863 Å line (Solf and Ulrich 1985), and may well be present in the red and UV plates taken in 1960, 1970, and 1980 (Sopka *et al.* 1982) but undetectable because of contamination from the bright core. Feature S is certainly part of the southern loop structure observed in the UV (Mauron *et al.* 1985), and in the UV and  $R$  bands from 1960 onwards (Sopka *et al.* 1982).

Feature B has obviously undergone some morphological changes in the last 20–30 yr. It is presently coincident with the peak flux position of the extended emission region observed in the radio (Hollis *et al.* 1985), UV (Mauron *et al.* 1985),  $V$  (Sol 1983), and  $[N\ II]$  6863 Å emission line (Solf and Ulrich 1985). It is quite likely associated with the bright spike of emission in broad-band  $R$  and UV plates in the NE (Sopka *et al.* 1982), taken in 1980. It is also clearly coincident in position and morphology with the unresolved feature B in the optical maps taken on 1984 January 20 by Hollis *et al.* (1985).

Our feature D of similar structure and intensity as feature B certainly did not exist as such as late as 1984 January 20, the date of the last high-resolution optical image taken by Hollis *et al.* (1985). Unfortunately, the  $H\alpha$  data published by Michalitsianos *et al.* (1988) does not have sufficient resolution and freedom from scattered light to allow a detection of such a feature if it had existed on 1986 October 1, two months before our observations. We conclude that it formed sometime between 1984 January 20 and 1986 November 28. We are not aware of high angular resolution radio observations of this area after 1984 February 3. It would be interesting to measure the area again to see if feature D has now a radio counterpart. In the 6 cm maps taken on 1984 February 3 by Hollis *et al.* 1985, there is an indication of a possible bulge forming in the expected position for our feature D that did not exist in the 6 cm map obtained on 1982 September 26. A similar remark could be made regarding the UV continuum map of Mauron *et al.* (1985). Finally, one should note the extraordinary coincidence of our feature D with the position of feature A seen in the 1960, 1970, and 1980 broad-band UV and  $R$  photographs of the nebula (Sopka *et al.* 1982). This coincidence clearly suggests that this feature has been there at least since 1960, but that it has varied considerably in brightness with respect to its neighbors in the last 30 yr.

In any case, the sudden appearance, or significant brightening, if one prefers, of feature D on a time scale of a few years or less, possibly following a period of relative stability, has interesting implications concerning the origin of the circumstellar material surrounding R Aqr and the excitation mechanisms that power the observed emission. The large relative intensity changes between features B and D and their physical proximity ( $\sim 300$  AU) strongly imply that the dominant source of emission in the jet is a local phenomenon, i.e., not the result of changing spatial or temporal conditions of illumination from the core, for example. The intensity and, possibly, the large-scale angular distribution of emitted flux from the central source may indeed fluctuate considerably even over relatively short time scales, but one would expect the relative intensity of the features B and D to remain about the same. It is difficult to

reconcile the results obtained so far with Spergel *et al.*'s suggestion that the jet appears because of the Mira shadowing effect for the same reasons. Substantial transfers of mass from one area of the nebula to the other on such time scales are also ruled out by the low radial velocities measured routinely and the very low upper limits obtained for the proper motion of any nebular feature.

Thus it is difficult to escape the conclusion that the emitting material has been around in approximately the present positions for a substantial interval of time, and the observed variations of relative intensity and morphology can only be due to a local phenomenon that affects one clump and not the others.

An important clue to the nature of this local phenomenon can be found in the  $[N\ II]/H\alpha$  line flux ratios in the features listed in Table 1. They range between  $1.2 \pm 0.1$  and  $1.8 \pm 0.1$ . Particularly significant are the ratios for features B and D of 1.8 and 1.3, respectively, that should be relatively uncontaminated by radiative transfer effects due to dust extinction or resonance scattering (Kafatos *et al.*). The quoted values of the  $[N\ II]/H\alpha$  line ratio can be used to discriminate between several possible excitation mechanisms of the emitting plasma. This can be accomplished by comparing them to the expected values for the following four possible mechanisms: photoionization by O and B stars as expected in a typical H II region, photoionization by the central stars of planetary nebulae, photoionization by a shallow power-law continuum and, finally, by shock-wave heating (see, e.g., Baldwin, Phillips, and Terlevich 1981).

The observed  $[N\ II]/H\alpha$  ratios for features B and D are a factor of 3–4 larger than the ratio expected for both a normal H II region and a planetary nebula and is quite consistent with either power-law ionization or shock-wave heating excitation, or a combination of both. Assuming the  $[O\ III]\ 5007\ \text{\AA}/H\beta$  and  $[O\ II]\ 3727\ \text{\AA}/[O\ III]\ 5007\ \text{\AA}$  ratios measured by Wallerstein and Greenstein (1980) for feature B in 1977 have remained reasonably constant throughout the intervening period, we can add these values to our comparison giving us a second dimension to play with. This assumption seems justified by noting the consistency between the Wallerstein and Greenstein (1980)  $[O\ III]\ 5007\ \text{\AA}/[O\ III]\ 4363\ \text{\AA}$  measured ratio of 16.5 and the range of  $\sim 15$ –20 quoted for this ratio by Michalitsianos *et al.* (1988) for feature B in 1986 October. The points obtained this way in the 5007/4861 versus 6584/6563 and 6584/6563 versus 3727/5007 planes do not allow a clear and definitive separation of the two mechanisms for this feature, however.

Although one cannot *a priori* rule out a power-law photoionization mechanism for any of the jet features, there are no indications from UV spectroscopy (Kafatos *et al.*) or soft X-ray observations (Viotti *et al.* 1987) of an excitation source of this type for features A and B, at least. We know already that the dominant excitation mechanism for feature D cannot be an ionizing flux of radiation from the central source because of its large recent intensity variation with respect to feature B. We are thereby forced to conclude that all the available data point rather naturally to the shock heating mechanism as the localized source of the feature D emission and, possibly by association, a fraction if not necessarily all of the B emission as well.

This conclusion seems to confirm the suggestion made by Solf and Ulrich (1985) on the basis of high-precision radial velocity data that feature B may be a clump of gas heated by a recent deceleration process. If this is the case, perhaps the same shock front responsible for feature B has recently collided with

material in the region of feature D. This scenario is quite plausible since this latter clump may be just a few years away from B for a disturbance traveling at  $100 \text{ km s}^{-1}$ . It might prove difficult to explain the steadily rising UV line fluxes measured by Kafatos *et al.* due to cooling time considerations. It is at least conceptually possible, however, that part of the observed increase is due to the emergence of new features as shown in this work since the time period corresponding to their appearance is consistent with the time scale over which the high-excitation emission lines of He II and N V appeared in the jet.

Detailed models of radiative shocks have been developed for application to supernova shells (Shull and McKee 1979) and to bow shocks around Herbig-Haro objects (Hartigan, Raymond, and Hartmann 1987). These shock models predict optical and UV emission-line strengths in reasonable accord with the observations of jet features A and B (Wallerstein and Greenstein 1980; Kafatos *et al.*), provided the shock front velocity  $V_s$  is greater than  $\sim 150 \text{ km s}^{-1}$ . The observed presence of N V  $\lambda 1240$  and He II  $\lambda 1640$  emission, and the strong [N II]  $\lambda 6584$ /H $\alpha$  ratio are not produced in models with smaller shock velocities. The fast shock models reproduce most of the observed line ratios to within factors of 2 or 3. The largest discrepancy is the C III]  $\lambda 1908$  line, for which the predicted flux is  $\sim 10$  times weaker relative to C IV  $\lambda 1549$  than observed. The observed radial velocity of  $-64 \text{ km s}^{-1}$  for knot B relative to the Mira LPV (Solf and Ulrich 1985) is compatible with a shock front velocity  $V_s \sim 150 \text{ km s}^{-1}$ . However, the observed velocity width of the [N II]  $\lambda 6584$  line from knot B is only  $\Delta V_{\text{FWZI}} < 20 \text{ km s}^{-1}$  (Solf and Ulrich 1985). This narrow width may be a problem for the shock model unless the shocks are highly coplanar, since the velocity profile produced in a bow shock is characterized by  $\Delta V_{\text{FWZI}} \sim V_s$  (Hartigan *et al.*).

#### V. CONCLUSIONS

We have presented in this paper the first sub-arc second resolution, photometrically accurate flux contour maps of the inner R Aqr nebula in the emission lines of H $\alpha$  and [N II]  $6584 \text{ \AA}$  obtained at epoch 1986.91. The following conclusions can be drawn from these results.

a. Beyond an arcsecond and within  $\sim 10''$  of the nucleus, all the detectable flux in both emission lines is concentrated primarily in three distinct features (A, B, D in the NE) of comparable physical characteristics and one faint and diffuse feature (S and southern loops) in the south.

b. There may be a faint unresolved H $\alpha$  feature at  $4'', 306^\circ$  p.a.

c. Feature A is unresolved in  $0.9''$  seeing, while features B and D have a seeing-corrected FWHM of  $1.8''$ .

d. Features A, B, S and loops are coincident within the expected position errors with previously observed features in the inner nebula.

e. Feature D did not exist in the present configuration at epoch 1984.1, but may have been present but possibly fainter in plates taken in 1960 and 1970.

f. An upper limit to the proper motion of feature B is  $0.15 \pm 0.05 \text{ arcsec yr}^{-1}$  corresponding to velocities less than or equal to  $140 \text{ km s}^{-1}$  at  $200 \text{ pc}$ .

g. The derived [N II]/H $\alpha$  flux ratios of 1.2–1.8 for the features in the inner nebula are consistent with a power-law photoionization or shock-heating excitation or both and are not consistent with photoionization by O, B stars, or central stars of planetary nebulae.

h. The recent brightening of feature D with respect to B indicates that the excitation source for the former is local.

i. Conclusions (g) and (h) together imply that line emission from feature D is most likely due to a shock wave traveling through a preexisting stationary clump of circumstellar material as suggested for feature B by Solf and Ulrich (1985).

It is clear from the results of this and previous work in the R Aqr nebula that it is the site of very complex and time variable phenomena that are difficult to understand with the haphazard spectral and temporal coverage carried out so far. Much more systematic work needs to be carried out to gain a clearer perspective. The technique we have described offers enormous potential for the accomplishment of this objective. The nebula needs monitoring on at least a yearly basis through a wide range of emission lines that are excellent diagnostics of the emitting plasma and the excitation mechanisms. These include, in addition to the ones used here, [O I],  $\lambda 6300$ , [O III]  $\lambda 5007$ , H $\beta$ , He II  $\lambda 4686$ , [O III]  $\lambda 4363$ , and [O II]  $\lambda 3727$ .

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