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THE R AQUARII NEBULA

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ABSTRACT

Photoelectric observations have been made of the emission line fluxes of the R Aqr Nebula on 16 nights for the period 1977 July 20 to 1979 November 15, with apertures between 16″ and 4′. The total Hβ flux was variable and showed changes of up to a factor of 2.5. The mean total Hβ flux for this period was 9.4×10^{-12} ergs cm^{-1} s^{-1}; 80% of this radiation is observed within the 16″ aperture. The Hα/Hβ ratio indicates a high degree of reddening, $c(\text{H}\beta)=0.88\pm0.12$. However, the published ultraviolet continuum cannot be fitted to a hot blackbody with the standard UV reddening function and any value of c. The λ2470 (from published data)/λ3727 [O II] ratio indicates 7×10^4 cm^{-3} $(c=0.4)<N_e<3\times10^5$ cm^{-3}$(c=0.88)$. The mass of the central nebula is about 10^{-5} $M_\odot$, and there appears to be a strong concentration toward the inner second of arc. The effective temperature and luminosity of the exciting source is estimated from standard radiative considerations to be 50,000–60,000 K, with $5<L/L_\odot<20$; the apparent magnitude is calculated to be about 15 in both B and V. A knot of gas 40″ east of R Aqr exhibits a spectrum whose excitation is much lower than that of the central nebula. B and V magnitudes near 3 minima for R Aqr itself are also presented.

Subject headings: nebulae: individual — stars: individual — stars: long-period variables

I. INTRODUCTION

R Aquarii is one of the more bizarre astronomical objects. The central star is a Mira variable surrounded by a delicate emission nebula with a diameter of about 2′. Most of the nebula is concentrated into an inner core about 30″ across. The stellar spectrum shows a variable blue component, which presumably is linked with the ionization of the nebula. The spectrum of the nebula is discussed by Merrill (1940) who also presents Hubble's 1939 photograph of the nebula. A number of papers have appeared since that time which discuss the stellar spectrum and the infrared and radio spectrum of the object. R Aqr and its nebula have been the subject of much recent attention. Michalitsianos, Kafatos, and Hobbs (1980, hereafter MKH) observed the ultraviolet lines and continuum with the *IUE*, as did Johnson (1980, 1981), who in the 1980 paper also discusses optical line profiles. Wallerstein and Greenstein (1980, hereafter WG) examined the optical spectrum and continuum. Johnson (1980) and WG also present good summaries of previous work.

When this study was begun in 1977, no one had yet measured the total absolute Hβ flux from the object, although Johnson (1980) and WG now give absolute fluxes for restricted apertures. After 3 nights of observation with the wide (4′) aperture, over a 3-month period, it was found that the total Hβ flux was variable. The study was thus extended over three observing seasons to examine the nature of the variability and any relation it might bear to the behavior of the central star. Some other prominent emission lines were also examined, and the knot of gas to the east of the star was studied as well.

II. THE OBSERVATIONS

The star and nebula were observed with the University of Illinois 1 m reflector at Prairie Observatory with a single channel photometer and a red-sensitive RCA photomultiplier tube operating in a pulse-counting mode. The nebular spectrum lines λ6584 [N II], Hα, λ4959 [O III], Hβ, and λ3727 [O II], plus continuum points at λ6503, λ5500, and λ4428, were isolated by means of interference filters. The details of the observation and reduction are described by Kaler (1976*a*, 1980).

All the emission lines except λ3727 [O II] were separated from the underlying continuum by linearly interpolating between (or extrapolating from) the three continuum points. The emission lines within the continuum filter pass bands, notably λ4414 [Fe II] (see WG), produce a negligible effect on the emission line fluxes, although they have a significant effect on the derived B magnitude (see below). The strength of the emission lines compared to the continuum and the near linearity in the continuum between λ5500 and λ4428, as determined from WG, renders the procedure accurate to within about ±5% (about ±10% for λ4959). The λ3727 flux is an average of that derived from a linear continuum extrapolation (which produces the maximum

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value) and that found from a continuum derived from WG's work (which produces the minimum value).

Results are presented for each of the 16 nights in Table 1. Columns (1) and (2) give the date and Julian day, and column (3) gives the aperture size used. Column (4) presents the observed $F(H\beta)$ in ergs cm^{-2} s^{-1}, calibrated with Barker's (1978) fluxes of planetary nebulae. Columns (5) and (6) show the relative intensities for λ4959 [O III] and $I(\lambda 3727)$ [O II] on the scale $F(H\beta)=100$, uncorrected for reddening. The errors are derived from the statistics of the counts only, and do not include external sources; those for $I(\lambda 3727)$ include the uncertainty in the underlying continuum. Finally, columns (7) and (8) give B and V magnitudes for R Aqr itself for diaphragm sizes of 40″ or less. These are derived from the continuum filter observations and are not corrected for nebular continuum or for weak emission lines, consistent with general photometry practice for this star. The correction to a "true" stellar magnitude averages about 0.3 mag for B and is less than 0.1 mag for V.

The averaged intensities and Hβ flux are shown in Table 2 for two different aperture ranges. The table also shows the mean intensities of the Hα line and λ6584 [N II], which were observed on 3 nights in the 40″–4′ range and on 1 night with the 16″ aperture. The spectrum of a knot of gas 40″ east of the star, observed with the 26″ aperture, is given in the last column of Table 2.

III. DISCUSSION

a) The Spectrum of the Central Nebula: Fluxes and Variability

The major feature of Table 1 is the variability of $F(H\beta)$, which is qualitatively similar to the degree of variability in the radio emission found by Gregory and Seaquist (1974). In the three observing seasons, it varied from a high of 13.4×10^{-12} ergs cm^{-2} s^{-1} to 5.06×10^{-12} ergs cm^{-2} s^{-1}, far in excess of the errors. $F(H\beta)$, B, and V are all plotted against time (JD) in Figure 1. $F(H\beta)$ is plotted with the left-hand axis with open symbols which represent different aperture sizes; B and V are plotted with the right-hand axis. Taken by themselves, the $F(H\beta)$ exhibit no pattern or periodicity. There does seem to be a possible qualitative relation between $F(H\beta)$ and B and/or V. Note from Figure 1 that the fluctuations tend to go in the same direction. However, this relation is far from certain. An examination of periodicity or of relation with stellar variability is confounded by the fact that R Aqr is observable for only 5 1/2 months at a time and currently only near stellar minimum. The Hβ flux observed with the 40″ aperture is within the errors of that with the 4′ aperture, showing the strong concentration of luminosity to the center of the nebula (see Table 1, 1978 July 5); consequently, the 4′ and 40″ observations are averaged for

TABLE 1
OBSERVATIONS OF R AQUARII

Date (1)	JD (244+) (2)	Ap (3)	10^{12} $F(H\beta)$ (ergs cm^{-2} s^{-1}) (4)	$I(\lambda4959)$ [O III][a] (5)	$I(\lambda3727)$ [O II][a] (6)	B (7)	V (8)
1977 Jul 20	3345	4′	8.00±0.89	...	...	...	...
1977 Aug 24 ...	3380	4′	8.04±0.30	72±14	148± 8	...	...
1977 Sep 27 ...	3414	26″	5.85±0.29	71±11	65±12	13.7±0.2	12.61±0.02
1977 Oct 3 ...	3420	4′	9.87±0.37	85±17	150±10	...	...
1977 Oct 14 ...	3431	4′	9.55±0.21	...	...	...	...
1977 Oct 14 ...	3431	16″	6.97±0.05	95± 2	...	...	12.35±0.02
1977 Oct 18 ...	3435	4′	10.0 ±0.5	...	...	...	...
1978 Jul 5	3695	4′	13.1 ±0.7	58±21	...	13.0±0.2	11.49±0.02
1978 Jul 5	3695	40″	12.9 ±0.2	71± 8	...	...	...
1978 Jul 13	3703	4′	13.4 ±0.2	101± 7	136±20	...	...
1978 Aug 22 ...	3743	4′	8.7 ±1.9	...	...	...	...
1978 Aug 22 ...	3743	40″	6.55±0.39	79±17	175±15	13.7±0.2	12.39±0.03
1978 Sep 6 ...	3758	4′	10.2 ±0.4	88±12	...	...	...
1978 Sep 18 ...	3770	40″	8.8 ±0.2	65±14	...	13.6±0.4	12.60±0.08
1978 Sep 18 ...	3770	16″	7.52±0.08	63± 3	...	13.3±0.1	12.46±0.03
1978 Oct 23 ...	3805	4′	9.22±0.33	78±12	...	...	...
1978 Dec 16 ...	3860	40″	10.2 ±0.2	125± 9	...	12.5±0.1	10.43±0.02
1979 Sep 14 ...	4131	4′	9.7 ±0.8	130±37	...	...	11.64±0.01[b]
1979 Oct 25 ...	4172	40″	6.66±0.21	118± 8	...	13.1±0.1	11.75±0.02
1979 Nov 15 ...	4194	40″	5.06±0.48	351±36	...	13.7±0.1	11.88±0.02

[a] $I(H\beta)=100$.
[b] 40″.

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TABLE 2

CHARACTERISTIC SPECTRUM OF R AQUARII AND EAST NEBULAR KNOT

λ (1)	ID (2)	4′–40″ (3)	26″–16″ (4)	E Knot[b] (5)
6584	[N II]	23 ± 5	< 10[a]	415 ± 159
6563	Hα	550 ± 65	621 ± 12[a]	390 ± 206
4959	[O III]	89 ± 7	76 ± 10	< 50
4861	Hβ	100	100	100
3727	[O II]	150 ± 10	65 ± 12	281 ± 96
10^{12} log F(Hβ) ...	...	9.4 ± 0.6	7.5 ± 0.7[a]	0.11 ± 0.02
c	...	0.88 ± 0.12		0.41 ± 0.55

[a]16″ aperture.
[b]40″ E, 3″ N of star, 26″ aperture.

Table 2. However, the Hβ flux is significantly diminished through the 16″ aperture. From 1977 October 14 and 1978 September 18, $F(16'')/F(4', 40'')=0.79$; this ratio was applied to the mean (4′–40″)Hβ flux in column (3) of Table 2 to derive that for column (4), appropriate to the 16″ aperture.

The total range of variation in Hβ is not known. The mean Hα flux derived from Table 2 is 7.6 times larger than that given for 1975 August by Johnson (1980), considerably in excess of the factor of 2.5 variation observed in this study. The Hβ flux observed by WG through a 10″ aperture in early 1977 September is similar to the bracketing observations in Table 1, implying strong concentration to the center. The Hβ flux inferred from WG's Table 2 is roughly twice the corresponding Prairie observations. Sudden changes in flux may be possible. Such changes might not be surprising, since the nebula is strongly concentrated to the inner second of arc (see above and § III*b*), for which the light travel time is less than 2 days.

Because of the variable nature of the nebula, it is not possible to compare accurately the above Hβ fluxes with Gregory and Seaquist's (1974) 10.5 GHz or Johnson's (1980) 85 GHz flux densities, since they were not made simultaneously. The ratio of the average of the two 10.5 GHz observations with the average Hβ flux is 2.5 times larger than that predicted from the calculations of Oster (1961) and Brocklehurst (1971) at 10^4 K; the 85 GHz/Hβ ratio is 39 times too large. The differences can at least in part be ascribed to extinction of Hβ by dust (see § III*b*) and, given the still unknown amplitude of variation, are not inconsistent with a simple steady-state thermal/recombination origin of the radiation, although more complicated physics certainly cannot be ruled out.

An observation of F(Hβ) was obtained on 1978 December 16, which is close to the date (1978 December 4) that Johnson (1980) made his *IUE* observations. Since F(Hβ) for October 23 and December 16 are similar, the latter probably applies well to the date of Johnson's (1980) observation. He used a 10″×20″ aper-

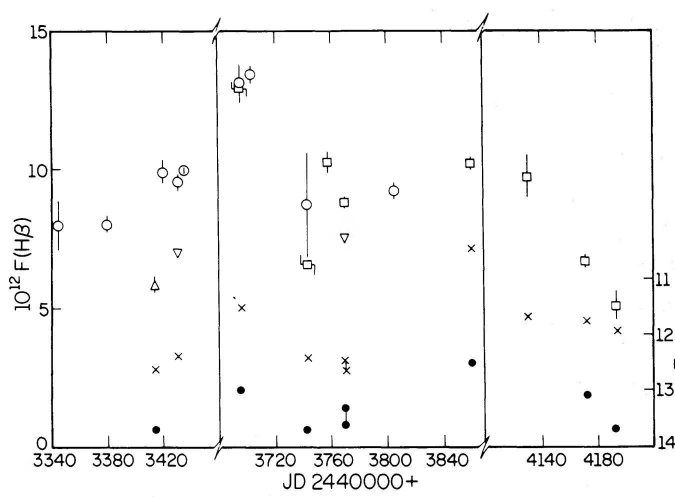

FIG. 1.—F(Hβ) of the R Aqr Nebula and the magnitude of R Aqr as a function of time (Julian Date). The open symbols show F(Hβ) in ergs cm^{-2} s^{-1} plotted against the left-hand scale for the following aperture sizes: *circles*, 4′; *boxes*, 40″; *upward triangles*, 26″; *downward triangles*, 16″. Stellar magnitude is plotted against the right-hand scale for *B* (*filled circles*) and *V* (*X's*).

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ture, which has nearly the same area as the 16″ aperture used at Prairie and, since the radiation is strongly concentrated to the center, can be considered exactly equivalent. Thus, his observations can probably be calibrated to Hβ and to the optical spectrum by multiplying $F(\mathrm{H}\beta)$ for December 16 from Table 1 by 0.79, the ratio of the 16″ flux to the 40″ flux, so that $F(\mathrm{H}\beta)$ (Johnson, December 4)$=8.1\times10^{-12}$. However, note the possibility of sudden variations discussed above.

The $I(\lambda4959)/I(\mathrm{H}\beta)$ ratio also appears to show some fluctuation but, for the most part, not outside the error bars. $I(\lambda4959)$ is higher for the last 4 nights and appears to be quite high for 1979 November 15, possibly indicating a secular trend. A spectrum taken by Michalitsianos on 1979 December 7 (private communication) shows $I(\lambda4959)\approx80$, similar to the majority of entries in the table. The fluctuations in $I(\lambda4959)$ show no correlation with any other parameter. On the whole, the spectrum of the central nebula is typical of a lower excitation planetary such as IC 2149.

b) *Properties of the Nebula: Dust, Density, and Mass*

Calculations of the physical properties of the nebula and exciting star are replete with inconsistencies. However, it is interesting to make at least an attempt at them, given some basic simple assumptions. The high Hα/Hβ intensity ratio, which agrees with that found by WG, suggests that the light from the nebula and star is heavily reddened. But, as pointed out by WG, a high degree of reddening is inconsistent with the stellar colors, which show no effects of reddening. This anomaly is confirmed by the stellar photometry of Barnes (1973) and by an analysis by Cahn (private communication).

If we assume that the nebula is in radiative equilibrium, which may not be correct, and use the normal Hα/Hβ ratio of 2.85 (Brocklehurst 1971) and the Whitford (1958) reddening function, the logarithmic Hβ extinction, c, is 0.88 ± 0.12. This value corresponds to $A_v=1.9\pm0.3$ mag, in agreement with WG. The dust, if this procedure is correct, must be circumstellar, since $b=70°$. The fact that R Aqr is indeed surrounded by some kind of dust shell is supported by the high infrared flux observed by Stein *et al.* (1969) and by the high degree of polarization found by Serkowski (1974).

Other anomalies appear when we try to deredden the published ultraviolet continuum flux densities. If we use the Bless and Savage (1972) and Nandy *et al.* (1975) reddening functions, Johnson's (1980) λ2150/λ3000 flux ratio is 3 times that expected from a blackbody in a temperature range of 50,000–60,000 K indicated by the nebular spectrum (see below). The energy distribution longward of 2100 Å is in better accord with a blackbody if the λ2200 bump is smoothed out. Also, Johnson's (1980) and WG's continua can be fitted (to within about ±25%) to a blackbody if c is 0.40–0.45, with the λ2200 bump intact. However, MKH show that the observed continuum remains flat down to 1300 Å, which is then undercorrected by any of the above dereddening schemes. Further discussion is precluded by the uncertainty of the correct reddening function and the exact radiation mechanism.

The density of the central nebula can clearly be very high, but a large range is also seen. WG find $3\times10^5<N_e<5\times10^6$ cm^{-3} from the [O III] line intensities and $3\times10^3<N_e<3\times10^5$ cm^{-3} from [O I] and well over 10^6 from [N II]. WG's observations of [S II] yield 10^4 cm^{-3}. Johnson (1981) finds $N_e<4\times10^5$ cm^{-3} from C III]. Ilovaisky and Spinrad's (1966) estimate of the [O II] λ3728/λ3729 ratio produces the lowest value, only 10^3 cm^{-3}. It is likely that we are dealing with a seriously inhomogeneous nebula with a strong density gradient.

The results of this paper allow us to add one more line pair pertinent to density measurement, the [O II] transauroral/nebular (λ2470/λ3727) ratio. MKH observe a λ2470 flux of 1.9×10^{-12} ergs cm^{-2} s^{-1}. This flux should be increased by about 20% in order to scale it to Johnson's (1980) data, which are appropriate to $F(\mathrm{H}\beta)=8.1\times10^{-12}$ ergs cm^{-2} s^{-1} from § III*a* above. From Table 2, column (4), we then find that $F(\lambda3727)=5.3\times10^{-12}$ ergs cm^{-2} s^{-1}, and thus the unreddened λ2470/λ3727 ratio is 0.43. The electron density is found from the calculations of Saraph and Seaton (1970) and is of course sensitive to both electron temperature and the uncertain reddening. The assumption is made that the reddening is bracketed by the optical value of $c=0.88$, and $c=0.4$ inferred from the near ultraviolet continuum; the latter is at least appropriate to the wavelength region which contains the [O II] lines. From WG's Balmer continuum/Hβ ratio, and the recombination coefficients of Brown and Mathews (1970) and Brocklehurst (1971), $T_e=7500$ K and 12,000 K for $c=0.88$ and $c=0.42$, respectively, and the corresponding electron densities are 3×10^5 cm^{-3} and 7×10^4 cm^{-3}. If $c=0$, T_e from the Balmer continuum seems unreasonably high ($\approx$20,000 K), and $N_e=3\times10^4$ at $T_e=12{,}000$ K. These densities are in the range found by WG and Johnson (1980), but are again not consistent with the [O II] density found by Ilovaisky and Spinrad (1966).

Given the uncertainties in c, N_e, and T_e, little can be said here about the abundances, but they can be used as a check on the above. The (26″–16″) [O II] data can be made consistent with a high density and reasonable O/H ratio. However, N^+/O^+ from the (4′–40″) data (see Table 2) is too low unless N_e approaches 10^3 cm^{-3}; much the same can be said for the smaller aperture data, since λ6584 was not even detected. Note, however, that WG find a reasonable N/O from their small aperture data. Possibly the λ3727 flux of Table 2 is not compatible with the λ2470 flux, and the densities derived above are incorrect. The different line ratios and densities, and the many inconsistencies, indicate that the construction of a realistic model will be a difficult task.

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The analysis confirms that most of the radiation seems to come from a small volume. If we adopt a distance of 260 pc from Baade (1943) and an angular radius of 8″ corresponding to the smallest aperture (and appropriate to the visible central nebulosity, see Merrill 1940), the rms density from the Hβ flux and $c=0.88$ is only 5.4×10^3, which implies a tiny filling factor. Only if the volume of radiating matter is of the order of 1″ or less in radius does the rms density approach the [O II] density derived from the transauroral/nebular ratio, which is consistent with the small radius and high rms density ($6\times10^4<N_e<2\times10^5$) discussed by Gregory and Seaquist (1974).

For a given distance, the nebular mass is dependent almost entirely upon N_e and $F(\mathrm{H}\beta)$. From the [O II] density above and the observed Hβ flux, the mass is found to be $1.3\times10^{-5}\ M_\odot$, similar to that derived by Gregory and Seaquist (1974). For the different values of c, the variations in N_e and $F(\mathrm{H}\beta)$ nearly cancel one another. These calculations of course assume Hβ to be strictly due to recombination. Certainly, however, the strong gradients and inhomogeneities discussed above render any discussion of mass quite approximate.

c) *The Exciting Source*

If we assume that the nebula is excited by photoionization from the hot blackbody, we can use the nebular radiation to deduce some of the parameters of the exciting source. In the following, the effects of internal dust, which are probably significant, are ignored. The extinction is presumed to be caused by dust external to the nebular core. The temperature of this source ($T_\star$) can be estimated from the λ4959 [O III]/Hβ intensity ratio and the relation presented by Kaler (1978). From Table 2 alone, $T_\star=35{,}000$ K. However, λ4959 is certainly depressed because of collisional de-excitation. If $N_e=10^6$ cm^{-3} is appropriate for the [O III] emitting region (see WG), a solution of the O^{2+} balance equations show that λ4959 should be multiplied by a factor of 2.8 and, consequently, that $T_\star=50{,}000$ K. The presence of weak He II observed by WG indicates that $T_\star\sim60{,}000$ K (see Kaler 1976*b*). Given the uncertainty in density, the two values are in good agreement.

From $T_\star$, the observed Hβ flux, and the formulation of the Zanstra method developed by Harman and Seaton (1966), we can derive the luminosity and apparent magnitude of the exciting source. For the mean Hβ flux observed and the given range in c and $T_\star$, the luminosity is found to be $5<L/L_\odot<20$, which would place the source just to the low-mass side of Paczyński's (1970) 0.6 $M_\odot$ cooling track. For $T_\star=50{,}000$ K, $c=0.88$, and $F(\mathrm{H}\beta)=9.4\times10^{-12}$ (Table 2), $B=15.0$ and $V=14.3$. An assumption of 60,000 K makes both B and V about 0.5 mag fainter. The observed minimum-light B and V from Table 1 are 13.7 and 12.6, respectively, so that even at minimum the observed optical starlight is dominated by the M star. Thus, an exciting source at 50,000–60,000 K is consistent with most of the observations and with the observed color of the M star. However, it is not consistent with the far-UV observations of MKH as corrected by standard reddening techniques. The subject of the exciting source is far from closed. This discussion refers only to the averages over the three observing seasons. The variability of $F(\mathrm{H}\beta)$ and of the λ4959/Hβ ratio (see especially the last entry in Table 1) shows that the exciting source is variable as well.

d) *The East Knot*

The last column of Table 2 presents the spectrum of the knot of gas 40″ E and 3″ N of R Aqr at the intersection of the two loops, observed with the 26″ aperture. The nebula here is of much lower excitation, as seen by the large increases in [N II] and [O II] line strengths and the undetected [O III]. Unfortunately, the error in Hα is too high to allow any meaningful discussion of extinction. The Hβ flux from the knot is some 85 times less than that from the central nebula, implying a lower electron density. At $c=0.41$, $N_e=270/\sqrt{\varepsilon}$, where the filling factor ε is unknown. The [N II]/[O II] ratio is consistent with normal N/O at low density and T_e in the neighborhood of 10^4 K.

IV. SUMMARY

The absolute Hβ flux radiated by the R Aqr Nebula is variable, with a range in amplitude of a factor of 2.5 over three observing seasons, qualitatively similar to the variation in the radio flux found by Gregory and Seaquist (1974). Larger and possibly sudden variations are indicated by comparison with other observations. No convincing relation between $F(\mathrm{H}\beta)$ and any other parameter can be found, although a qualitative correlation with stellar magnitude may be present.

The Hα/Hβ ratio agrees with that found by Wallerstein and Greenstein (1980) and indicates high extinction ($c=0.88$). However, an extinction this high and the standard reddening function strongly overcorrects Johnson's (1980) ultraviolet continuum fluxes near 2100 Å and undercorrects MKH's far-UV fluxes. The reddening constant and function seem highly uncertain.

The [O II] λ2470/λ3727 ratio from MKH and this paper leads to high electron density (7×10^4 cm$^{-3}<N_e<3\times10^5$ cm^{-3}) in reasonable accord with densities found by Wallerstein and Greenstein (1980), Gregory and Seaquist (1974), and Johnson (1981), but in serious disagreement with the low value of 10^3 cm^{-3} suggested by Ilovaisky and Spinrad (1966) from the λ3726/λ3729 [O II] ratio. The high [O II] density is also incompatible with the observed low $I(\lambda6584)/I(\lambda3727)$ ratio.

If the true density is high, the rms electron density calculated from the Hβ flux leads to extremely low filling factors, unless most of the radiating mass is

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concentrated to a central region with a radius of 1″ or less. Such a concentration is supported by a variety of flux measurements. The mass of the central nebula is of the order of 10^{-5} $M_{\odot}$.

If the nebula is excited by photoionization, the effective blackbody temperature of the exciting source was in the neighborhood of 50,000–60,000 K, as deduced from the λ4959/Hβ ratio and the presence of He II λ4686 observed by Wallerstein and Greenstein (1980). From this temperature, the above extinctions, and the Hβ flux, the luminosity of the source is $5 < L/L_{\odot} < 20$, and we would expect it to be no brighter than $B \approx 14.5$ and $V \approx 14.3$, both of which are significantly fainter than the observed star at extreme minimum.

In spite of the recent efforts, the R Aquarii Nebula still presents a confused picture. The high Hα/Hβ ratio, which indicates a high extinction (on the assumption of recombination theory), is not consistent with the ultraviolet continuum fluxes, nor is it consistent with the color of the M star which indicates a low extinction. Different ions or even line pairs from the same ion give very different densities, suggesting the presence of great inhomogeneity and strong density gradients. Clearly, this object will provide considerable opportunity for continued observational and theoretical work.

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