

## IUE OBSERVATIONS OF CIRCUMSTELLAR EMISSION FROM THE LATE TYPE VARIABLE R AQUARI (M7 + pec)

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### ABSTRACT

*IUE* observations of R Aquarii (M7 + pec) have been obtained in low dispersion in order to study its circumstellar emission. Strong permitted, semiforbidden, and forbidden emission lines are identified that are superposed on a bright ultraviolet continuum. From our analysis we deduce that the strong emission-line spectrum that involves C III], C IV], Si III], [O II], and [O III] probably arises from a dense compact nebula the size of which is comparable to the binary system of which R Aqr is the primary star. Low-excitation emission lines of Fe II, Mg II, O I, and Si II suggest the presence of a warm chromosphere ( $T \lesssim 10,000$  K) in the primary M7 late type giant. We identify the secondary as a white dwarf, comparable to or somewhat brighter than the Sun, since such a star can produce enough ionizing photons to excite the continuum and emission-line spectrum and yet be sufficiently faint to escape detection by direct observation. The UV continuum observed is attributed to Balmer recombination and not to blackbody emission from the hot companion. The general spectral properties of R Aqr between 1200 Å and 3200 Å are discussed in the context of our model for the circumstellar nebula, the companion, and the mass-loss rate of the primary star.

*Subject headings:* stars: binaries — stars: circumstellar shells — stars: individual — stars: long-period variables

### I. INTRODUCTION

Ultraviolet observations of the late type star R Aquarii (M7 + pec) have been obtained with the *International Ultraviolet Explorer (IUE)* and reveal intense emission lines and continuum. This confirms the conclusions drawn from earlier optical observations made by Merrill (1921, 1935, 1950) that a hot stellar companion coexists with a relatively cool late type star. Low-dispersion spectra between 1200 Å and 3200 Å show strong permitted emission lines of C IV (1548, 1550 Å), Si III] (1883, 1892 Å), C III] (1907, 1909 Å), and Mg II (2796, 2803 Å). Forbidden emission lines of [O II] (2470 Å) and probably [O III] (2321 Å) are also detected in the UV and are consistent with lines of [O III] (5949, 5007 Å) and [O II] (3726, 3729 Å) observed in the optical spectrum by Merrill (1950) and Ilovaisky and Spinrad (1966).

Additionally, the bright emission-line spectrum is accompanied by a general UV continuum, the intensity of which appears independent of wavelength over the spectral range observed. We attribute the origin of this continuum mainly to hydrogen recombination rather than H I two-photon emission. Accordingly, [O II] and [O III] forbidden emission lines and the UV continuum most likely originate from a compact

nebula of limited extent ( $\lesssim 10^{15}$  cm) and located in close proximity to the binary system.

This stellar system exhibits a multitude of varied emission properties, being identified also as an infrared source at 10 μm (Schmitz *et al.* 1978), as a variable radio source at 8.085 MHz, 2.695 MHz (Gregory and Seaquist 1974), and at 14.9 GHz (Bowers and Kundu 1979), and more recently as an SiO maser star at 43.12203 and 86.24327 GHz (Engels 1979; Zuckerman 1979).

The properties of the UV spectrum are discussed in § II, where we have estimated the temperature, density, and size of the ionizing nebula from absolute flux measurements in strong permitted and forbidden emission lines. Of particular interest in our observations is the distinct lack of a stellar UV continuum that should be present if an O- or B-type dwarf main-sequence star is the source of excitation in the nebula, as has been suggested by Merrill (1950). The continuum observed in our data does not adequately match that of a star. We find the continuum observed most likely originates from a low-excitation nebula with an electron temperature  $T \approx 15,000$  K. The source of excitation is a subluminescent, central planetary-nebula star or bright white dwarf of  $T_* \gtrsim 50,000$  K, whose orbit about the primary M7 star is comparable

to the size of the ionized nebula, i.e.,  $10^{14}$ – $10^{15}$  cm. The details of our conclusions are discussed in the following sections. Details of the *IUE* instrumentation are described by Boggess *et al.* (1978).

## II. DATA AND ANALYSIS

In Table 1 we give the probable identification of a number of prominent features in the spectrum of R Aquarii. Our low-dispersion spectra obtained with *IUE* have a spectral resolution of  $\sim 6$  Å and were taken using moderate exposure lengths of 10 and 20 minutes. Columns (1) through (4) in Table 1 identify the ion species that we have deduced as the most likely source of emission, the published wavelengths for the particular transitions, the wavelengths actually measured with the *IUE* spectrometer, and the absolute flux measured at the detector, respectively.

The absorption due to the interstellar medium can be estimated, since the distance to R Aqr is known. R Aqr lies  $\sim 245$  pc below the galactic plane at a distance of  $\sim 260$  pc from the Sun (Gregory and Seaquist 1974). The average hydrogen density along the line of sight is estimated at  $0.2 \text{ cm}^{-3}$ , on the basis of a mean density in the solar neighborhood of  $\sim 0.4 \text{ cm}^{-3}$  (cf. Falgarone and Lequeux 1973). Using the relation between hydrogen column density  $N_H$  and  $E_{B-V}$  from Spitzer (1978) and Bohlin (1975), we find  $E_{B-V} \approx 0.03$ . The "standard" cloud model parameters from Spitzer (1978) yield  $E_{B-V} \approx 0.1$ . The latter is probably an overestimate since it refers to line-of-sight absorption in the galactic plane. We adopt

$E_{B-V} \approx 0.05$ , which corresponds to 0.37 magnitudes of extinction for R Aqr at 1550 Å. In our analysis we have corrected for the fluxes shown in Table 1 for this small absorption effect.

The strong lines of He II, C II, C III, C IV, O I, [O II], O III, [O III], O IV, Mg II, S II, Si III, Si IV, and Fe II are evident in the spectrum (Figs. 1 and 2). The identification of N V and Si II 1304 Å, 1309 Å is doubtful because other lower excitation lines of nitrogen are not present, and similarly for silicon, Si II 1265 Å is not observed. A number of Fe II features in various multiplets are also identified. We have noted all ambiguous identifications with a question mark in Table 1.

The low-excitation lines of Fe II and Mg II have been observed in the spectra of single late type stars by Carpenter and Wing (1979), and the presence of the above lines, as well as O I and Si II, in the UV spectrum of R Aqr argues strongly for a cool chromosphere  $T \lesssim 10,000$  K for the primary M7 star (Linsky 1979). However, we assume from our analysis that the other high-excitation lines observed in our data do not arise from the companion directly. We attribute the formation of the majority of strong lines to a compact nebula that is excited by emission from the hot companion. Adopting this model we can deduce the general properties of the nebula from the line and continuum emission.

The observed line fluxes can also be used to obtain the general parameters of the nebula. These parameters can then be checked against those derived from our analysis of the continuum that follows. We have used

TABLE 1  
ABSOLUTE FLUXES AND LINE IDENTIFICATIONS

Ion (1)	Wavelength (Å) (2)	Wavelength (Å) of <i>IUE</i> Feature (3)	Flux (ergs $\text{cm}^{-2} \text{s}^{-1}$ ) (4)	Comments (5)
{N v? + S II}	1230, 1243 1254, 1259	1247 (1240–1258)	$1.2 \times 10^{-12}$	Blended? N v identification unclear because of lack of observable N IV] 1486 Å and N III] 1750 Å features
{O I + Si II?	1302, 1305, 1306 1304, 1309	1304	$3.0 \times 10^{-13}$	Si II unclear because Si II 1265 Å should also be present
C II	1335, 1336	1336	$6.5 \times 10^{-13}$	
{Si IV + O IV]	1394, 1403 1400, 1401, 1405, 1407	1402	$1.4 \times 10^{-12}$	Blended feature?
Si II	1527, 1533	1527	$8.5 \times 10^{-13}$	Reseau mark in middle of feature; strongest lines of Si II
C IV	1548, 1551	1548	$2.7 \times 10^{-12}$	
He II	1640	1640	$10^{-12}$	
{O III] + Fe II?	1661, 1666 multiplets (68), (42), (40), (102), (41)	1668 (1654–1686)	...	Broad feature, probably Fe II multiplets because Fe II present in long-wavelength spectra
{Si III] + C III]	1883, 1892 1907, 1909	1892 1907	$3.0 \times 10^{-13}$ $2.6 \times 10^{-12}$	
{[O III] + C II]	2321 2325, 2327, 2328	2328 (2310–2340)	$3.0 \times 10^{-12}$	Blended feature
[O II]	2470	2474	$1.9 \times 10^{-12}$	
Fe II	2586–2631 multiplet (1)	2585–2640		Observed in other cool stars
Fe II?	2714–2770 multiplets (62), (63)	2735–2770	...	Identification plausible because these multiplets are almost as strong as (1). Total flux of feature $\sim 0.3$ of multiplet (1).
Mg II	2796, 2803	2802	$4.1 \times 10^{-12}$	

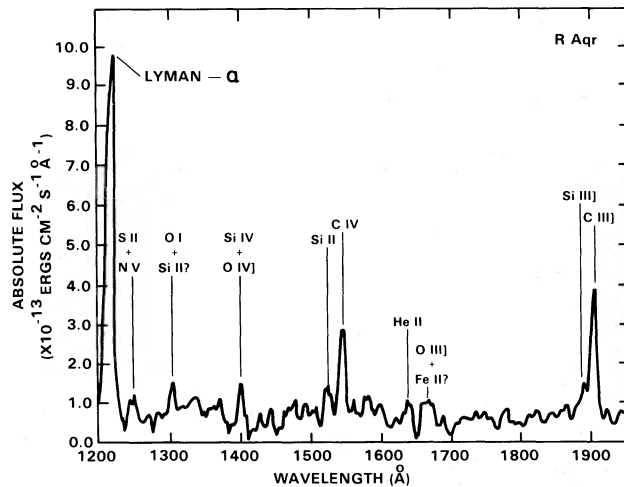


FIG. 1.—Low-dispersion ( $\sim 6 \text{ \AA}$  resolution) spectrum of R Aqr obtained on 1979 July 25 in the wavelength range 1200–2000  $\text{\AA}$  using the large aperture ( $10'' \times 20''$ ) of the *IUE* spectrometer. The exposure time on the SEC Vidicon camera was 10 minutes. The  $L\alpha$  line at 1216  $\text{\AA}$  has a combined intensity of the geocoronal and stellar  $L\alpha$  emission. The spectrum is deconvolved and geometrically and photoelectrically corrected. The absolute flux scale is accurate to a factor of 2 using the standard *IUE* reduction programs that have been developed at NASA-GSFC by Drs. Fahey and Klinglesmith.

the combined strengths of C II] (2325, 2327, 2328  $\text{\AA}$ ), C IV (1548, 1551  $\text{\AA}$ ), C III] (1907, 1909  $\text{\AA}$ ), [O II] (2470  $\text{\AA}$ ), [O III] (2321  $\text{\AA}$ ), and O IV] (1400, 1401, 1405, 1407  $\text{\AA}$ ). We have selected these lines because they represent various ion species, they are the strongest features in the spectrum, and there is little ambiguity in their identification. However, it is not clear if the 1402  $\text{\AA}$  feature is entirely due to O IV] and what portion of the broad 2328  $\text{\AA}$  feature is due to [O III] or C II].

#### a) Continuum

The observed continuum is essentially flat and rises slightly toward long wavelengths. At 2000  $\text{\AA}$  the continuum has a measured flux of  $\sim 5 \times 10^{-14}$  (ergs  $\text{cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$ ). The continuum cannot be due to a star, since a stellar blackbody continuum would vary with wavelength by more than an order of magnitude over the spectral range observed. However, Balmer recombination and H I two-photon emission arising from a nebula are mechanisms that may explain the continuum. Shortward of 3200  $\text{\AA}$  the two-photon continuum of hydrogen will dominate if the densities are sufficiently low ( $\lesssim 10^4 \text{ cm}^{-3}$ ) and will produce a prominent peak in intensity around 1400  $\text{\AA}$  (Bohlin, Harrington, and Stecker 1978). However, this peak is not observed in our data (Fig. 1), and we conclude that the two-photon process is not the dominant mechanism. On the other hand, the Balmer recombination continuum depends only weakly on temperature for  $T \approx 15,000 \text{ K}$ , and the flux  $F_\lambda$  varies only by a factor of 2 between 1200  $\text{\AA}$  to 3200  $\text{\AA}$ . Therefore, we conclude that this mechanism dominates and that the densities must be  $\geq 10^5 \text{ cm}^{-3}$ , since densities appreciably lower than this value would result in a conspicuous

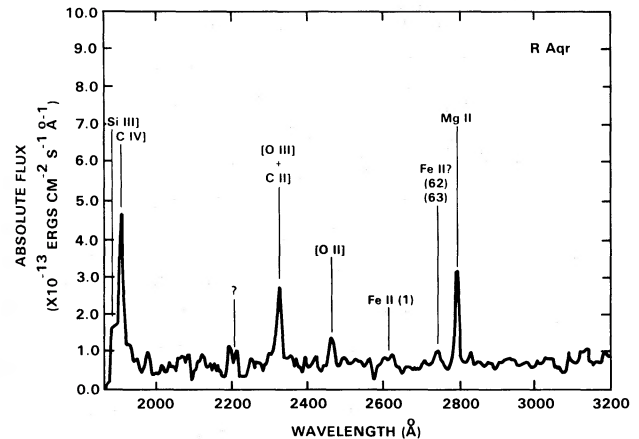


FIG. 2.—Low-dispersion spectrum of R Aqr between 2000 and 3200  $\text{\AA}$  obtained with the large aperture on *IUE*. Exposure time was 20 minutes. The feature identified with a question mark is probably an artifact in the detector. The continuum level is seen to rise slightly toward long wavelengths.

peak around 1400  $\text{\AA}$ . From this lower limit in density we deduce a corresponding upper limit of  $\sim 5 \times 10^{14} \text{ cm}$  for the size of the ionized nebula.

A further argument in support of a nebula with a characteristic size and density as that found above can be made from observations of visible emission lines by Merrill (1950). From radial velocity measurements of nebular lines Merrill (1950) found an orbital period for the hot companion of approximately 27 yr. The corresponding size of the semimajor axis for an elliptical orbit with this period is  $1.7 \times 10^{14}$  to  $2.1 \times 10^{14} \text{ cm}$ , for a mass ratio of 1:1 to 3:1, respectively, if the mass of the secondary is assumed to be  $1 M_\odot$ . If the ionized nebula was appreciably larger than the separation of the stars, one would not expect to observe substantial variations in line strengths. Ilovaisky and Spinrad (1966) have compared their visual spectral data of R Aqr to earlier observations of Merrill and found no evidence for a hot stellar companion whatsoever. From this they suggest the emission properties of the spectrum are probably time dependent. Merrill (1950) also found that the apparent position of the nebular emission appears to change. This is consistent with our model which suggests the ionized nebula is comparable in scale to the size of the binary orbit. Moreover, at a distance of 260 pc a central ionized cloud of scale size  $L = 2 \times 10^{14} \text{ cm}$  has a corresponding electron density of  $n_e = 1.5 \times 10^7 \text{ cm}^{-3}$ , which is sufficient to explain the recombination continuum observed. Additionally, the density implied by the continuum cannot be more than  $\sim 10^8 \text{ cm}^{-3}$ , since the size of the nebula would then have to be  $\sim 5 \times 10^{13} \text{ cm}$ , that is comparable to the estimated size of red giants, and therefore, unrealistic on physical grounds.

The densities obtained above from observations of the nebular continuum can also be roughly checked by the [O III] line strengths observed by Merrill (1950). He found that the 4363  $\text{\AA}$  line was unusually strong prior to 1934 and that “the ratio of its intensity to 4959  $\text{\AA}$  is equaled or exceeded in only one other



nebula, IC 4997." The intensity of the hydrogen lines relative to those of [O III] in R Aqr was similar to that observed in most planetary nebulae,  $H\beta$  being about equal to 4959 Å. After about 1922 the hot component started to dominate the spectrum for a few years, reaching a maximum in 1933–1934 (Mattei and Allen 1979). From the data of Aller and Liller (1966) we estimate the intensity ratio of 4363 Å to 5007 Å and 4959 Å to be  $\sim 0.1$  for the planetary nebula IC 4997 observed in 1922. Based upon the observations of IC 4997 (Aller and Liller 1966) and the statement of Merrill (1950) quoted above, it follows that the strength of the 4363 Å line in R Aqr prior to 1934 agrees with densities  $10^6 \lesssim n_e \lesssim 10^8 \text{ cm}^{-3}$  for temperatures  $3 \times 10^4 \gtrsim T \gtrsim 8 \times 10^3$ , respectively (Kafatos and Lynch 1980).

As shown above, the density deduced from the continuum observations cannot be  $\gtrsim 10^9 \text{ cm}^{-3}$ . A similar upper limit is implied by the oxygen line strengths, since the [O II] and [O III] lines would be suppressed and the 4363 Å line would be even stronger. It follows that the nebular parameters from the foregoing arguments are in the range  $10^5 \lesssim n_e \lesssim 10^8 \text{ cm}^{-3}$ ,  $10^{14} \lesssim L \lesssim 10^{15} \text{ cm}$ , and  $10^4 \lesssim T \lesssim 3 \times 10^4 \text{ K}$ . We adopt a model  $n_e \approx 10^7 \text{ cm}^{-3}$ ,  $L \approx 2 \times 10^{14} \text{ cm}$ , and  $T \approx 15,000 \text{ K}$ .

### b) Emission Lines

Here in § IIb we deduce the nebular parameters and the relative ionic abundances by two different methods: (1) by using the carbon line strengths and (2) by using the oxygen line strengths. We have assumed that the scale size of the nebula is  $L \approx 2 \times 10^{14} \text{ cm}$ , although the general trend of our results appears insensitive to this parameter (see Table 2). Parameters were computed from the C II], O IV], and He II intensities using Osterbrock (1963). Parameters were obtained from the C IV line intensities using Bely (1966) and from C III] using Osterbrock (1970). Parameters were also computed for the [O II] and [O III] line strengths using Kafatos and Lynch (1980), while the continuum intensity calculations were obtained from Osterbrock (1974). Furthermore, we have assumed normal cosmic abundances for the various elements under consideration (Cameron 1973).

#### i) Carbon Line Strengths

The semiforbidden lines of C II] and C III] and the allowed lines of C IV can be used with one another to find the product  $n_e^2 L^3$ . The flux at the detector for a particular emission line is

$$F = C n_e^2 B(n_e, T) N_{A,z} L^3, \quad (1)$$

where  $C$  is a constant involving distance, the correction due to extinction, and the abundance of the particular element  $A$ ;  $n_e$  is the electron density,  $B(n_e, T)$  is a factor dependent on temperature (and density for forbidden lines),  $N_{A,z}$  is the relative abundance of the ion  $Z$  of element  $A$ , and  $L$  is the scale size. For the carbon lines for densities less than or  $\sim 10^{10} \text{ cm}^{-3}$ ,  $B(n_e, T)$  is a function of temperature only, since

TABLE 2  
NEBULAR PARAMETERS ( $L = 2 \times 10^{14} \text{ cm}$ ,  $T = 15,000 \text{ K}$ )

Parameter	Value
Model A (Carbon Line Analysis)	
$n_e^2 L^3 \text{ (cm}^{-3}\text{)}$ .....	$4.4 \times 10^{55}$
N(C II).....	0.53
N(C III).....	0.32
N(C IV).....	0.15
$n_e \text{ (cm}^{-3}\text{)}$ .....	$2.3 \times 10^6$
N(O II).....	0.81
N(O III).....	0.19
N(He III).....	1
Flux ( $H\alpha$ ) (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$1.2 \times 10^{-12}$
Flux [O III] 5007 Å (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$1.5 \times 10^{-12}$
$F_{\text{continuum}}(2000 \text{ Å})$ (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$10^{-15}$
Model B (Oxygen Line Analysis)	
$n_e^2 L^3 \text{ (cm}^{-3}\text{)}$ .....	$1.25 \times 10^{57}$
N(O II).....	0.06
N(O III).....	0.86
N(O IV).....	0.08
$n_e \text{ (cm}^{-3}\text{)}$ .....	$1.25 \times 10^7$
N(C II) <sup>a</sup> .....	0.09
N(C III) <sup>a</sup> .....	0.55
N(C IV) <sup>a</sup> .....	0.36
N(He III).....	0.02
Flux ( $H\alpha$ ) (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$3.3 \times 10^{-11}$
Flux [O III] 5007 Å (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$5.5 \times 10^{-11}$
$F_{\text{continuum}}(2000 \text{ Å})$ (ergs $\text{cm}^{-2} \text{ s}^{-1}$ ).....	$2.0 \times 10^{-14}$

<sup>a</sup> See discussion in text.

collisional depopulation of the primary levels is unimportant. In Table 2 we have computed  $n_e^2 L^3$  and the relative ionic abundance N(C II), N(C III), N(C IV) under the assumption that

$$N(\text{C II}) + N(\text{C III}) + N(\text{C IV}) = 1$$

for  $T \approx 15,000 \text{ K}$ . It is essential that we identify the 2328 Å feature as C II], otherwise no self-consistent model can be constructed using the carbon lines (if the [O III] line is present, it cannot be more than  $\sim 0.1$  of the total intensity of the feature). The ionic abundance of N(O II) and N(O III) can then be obtained (the latter is an upper limit, since some O IV could also be present).

Since the He II 1640 Å recombination line does not strongly depend on temperature and essentially depends only on density, we can obtain the ionic abundance of He III by adopting cosmic abundance estimates for helium and by using the densities for the nebula that we have obtained from the carbon line analysis. We find that the ionic abundance of the He III ion would be large in this case, and all of the helium is essentially doubly ionized. We have deduced the  $H\alpha$  (6563 Å) and [O III] (5007 Å) line strengths as well as the flux of the continuum in Table 2 in model A. Although model A is not unique, it does indicate a general trend in our data. Reasonable ionic abundances for oxygen can be obtained if we use the carbon line strengths to obtain  $n_e^2 L^3$ . However, the densities would have to be generally lower than might be suggested by the strong [O III] 4363 Å line observed by Merrill (1950). Additionally, the computed flux

level of the continuum from model A is too low to explain the observed intensity measured in our data.

### ii) Oxygen Line Strengths

Assuming the 2328 Å feature is mainly due to [O III] and the 1402 Å feature is mainly O IV], one can use equation (1) to obtain values of  $n_e$  and  $T$ . Since  $B$  is now a function of  $n_e$  (i.e., collisional depopulation becomes unimportant above  $\sim 10^6$  cm $^{-3}$  for these forbidden lines), values of  $n_e$  obtained from a single temperature are not unique, but are relatively insensitive to temperature. A typical case is shown in Table 1 for  $T = 15,000$  K and  $L = 2 \times 10^{14}$  cm (model B). The continuum deduced from the line strengths of oxygen agree well with the observed continuum. Moreover, the deduced ionic abundance of He III agrees with the ionic abundance of O III (helium is essentially singly ionized, whereas oxygen is mostly doubly ionized).

On the other hand, if we use the cosmic abundance of carbon in this analysis, the line strengths of carbon should be a factor of  $\sim 50$  larger than observed. The only alternative is to assume that atomic carbon is underabundant by a factor of  $\sim 50$  in the ionized nebula. The depletion of carbon could be the result of the precipitation of carbon into grains, or possibly from the formation of CO that could result in oxygen-rich objects such as R Aqr. The relatively low abundance of carbon deduced in our analysis appears generally to be the case, since this result will not change even if parameters in Table 2 are varied (say the temperature is varied between 10,000 K and 15,000 K). At this point, however, it is not possible to distinguish between models A or B. It suffices here to say that model B appears more attractive since it does account for the continuum.

Additionally, it is of interest to note that the values of the nebular parameters deduced in our analysis, i.e.,  $L = 2 \times 10^{14}$  cm,  $n_e \approx 10^6$ – $10^7$  cm $^{-3}$ , and  $T \approx 15,000$  K, agree with the general parameters for nebular emission in symbiotic stars derived by Boyarchuk (1975).

The compact nebula could be entirely the result of mass loss from the primary star. Applying the equation of continuity and estimating the escape speed from the M7 giant to be  $\sim 24$  km s $^{-1}$ , which was obtained using the period-density relation for a period of

387 days and an assumed stellar mass of 1–3  $M_\odot$ , we find  $\dot{M} = 10^{-7} M_\odot$  yr $^{-1}$  for a nebula of radius  $r \equiv L/2 \approx 10^{14}$  cm and density  $n_e \approx 1.3 \times 10^7$  cm $^{-3}$ . This mass-loss rate is probably a lower limit since, as will be shown later, the hot companion is too faint to ionize the entire nebula. It is also unlikely that all the material lost by the star is still ionized.

### c) Properties of the Stellar Companion

We have already seen that the observed continuum cannot be due to a star and most likely arises from the nebula. However, since we have assumed that the source of excitation is a subluminescent star, the observed nebular continuum flux of  $10^{-13}$  ergs cm $^{-2}$  s $^{-1}$  Å $^{-1}$  places an upper limit to the flux that is contributed by the companion. In Table 3 we show the stellar parameters for the unseen companion if its flux contribution to the continuum is this upper limit.

In the first column of Table 3 we assume a temperature for the hot companion. The second column gives the corresponding stellar radius if the continuum at the detector is  $10^{-13}$  ergs cm $^{-2}$  s $^{-1}$  Å $^{-1}$  at 1200 Å. The third column gives the luminosity in solar units. Columns (4) and (5) give the absolute flux and the apparent visual magnitudes, respectively. The last column indicates the number of ionizing photons  $N_i$ (s $^{-1}$ ) emitted by the star.

This upper limit of continuum flux suggests a star whose apparent magnitude is too faint to be observed today. However, in 1934 it attained  $m_v \approx 8$  mag. In order for it to be observable today the continuum would have to be  $10^4$  times greater. The 1934 event, therefore, appears to have been an eruption of the hot companion that was not sufficiently strong to be classified a nova. It is possible that this eruption was triggered by mass transfer from the primary to the secondary.

We also note that the companion can ionize the dense nebula in the system. The stellar temperatures required are in the approximate range of  $10^5$  to  $1.5 \times 10^5$  K, although temperatures as low as  $5 \times 10^4$  K could be assumed if the density of the nebula were slightly lower than that shown in model B. It is most likely that the compact ionized nebula is "ionization bound" rather than "density bound," and therefore the mass-loss rate for the primary of  $10^{-7} M_\odot$  yr $^{-1}$  is

TABLE 3  
HOT COMPANION

$T_*(\text{K})$ (1)	$R_*/R_\odot$ (2)	$L_*/L_\odot$ (3)	$M_V$ (4)	$m_V$ (5)	$N_i(\text{s}^{-1})$ (6)
$1.5 \times 10^5$ .....	$4.1 \times 10^{-3}$	7.4	12.0	19.1	$4.3 \times 10^{44}$
$10^5$ .....	$5.6 \times 10^{-3}$	2.8	11.4	18.5	$2.0 \times 10^{44}$
$5.0 \times 10^4$ .....	$1.2 \times 10^{-2}$	0.75	10.1	17.2	$5.0 \times 10^{43}$

NOTE.— $T_*$  is stellar temperature.  $R_*$  is stellar radius.  $L_*$  is stellar luminosity.  $M_V$  is absolute visual magnitude.  $m_V$  is apparent visual magnitude.  $N_i$  is the number of ionizing photons emitted by companion.

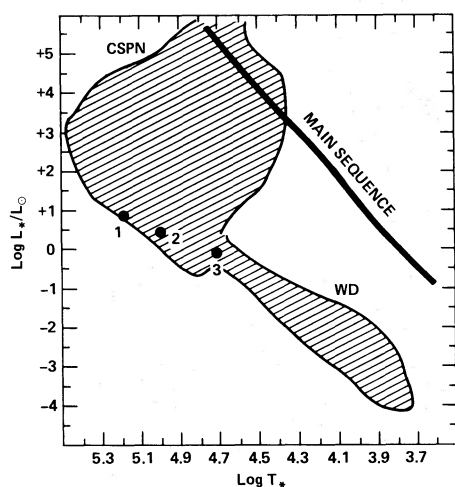


FIG. 3.—H-R diagram showing the main sequence, the region occupied by the central stars of planetary nebulae (CSPN) and white dwarfs (WD). The filled circles labeled 1, 2, and 3 give the location of the hot companion for  $T_* = 1.5 \times 10^5$ ,  $10^5$ , and  $5 \times 10^4$  K, respectively. Stellar parameters of the hot companion are shown in Table 3.

likely a lower limit. We also find that nebular temperatures greater than 15,000 K are required, for otherwise the density implied by the analysis based on the oxygen line strengths would be high, and a much brighter star would be required to ionize the nebula.

We find that the nebular parameters deduced from our oxygen line analysis are  $n_e \approx 10^7 \text{ cm}^{-3}$ ,  $1.5 \times 10^{14} \lesssim L \lesssim 2.5 \times 10^{14} \text{ cm}$  and that a companion having the parameters  $5 \times 10^4 \lesssim T \lesssim 1.5 \times 10^5 \text{ K}$ ,  $0.7 \lesssim L_* \lesssim 7 L_\odot$  can account for the nebular continuum, explain the fairly high-ionization state implied by the observed emission lines and provide sufficiently low stellar luminosity that the companion could not be seen directly. In Figure 3 we show the H-R diagram for the central stars of planetary nebulae (CSPN) and white dwarfs (WD) from Osterbrock (1974). The three filled circles labeled 1, 2, and 3 correspond to the stellar parameters of Table 3 for  $T_* = 1.5 \times 10^5$ ,  $10^5$ , and  $5 \times 10^4$  K, respectively. The hot companion appears to reside in the transition zone in the H-R diagram between the CSPNs and WDs and is essentially a bright white dwarf. The location of this star on the H-R diagram strengthens our belief that such a star is responsible for the ionization of the dense nebula, but itself is too faint to produce an observable continuum.

### III. DISCUSSION AND CONCLUSIONS

The optical spectrum of R Aquarii has puzzled observers for decades. The general light periodicity of the M giant has at times shown erratic behavior in luminosity, most notably between 1928 and 1934. During this interval the blue companion grew stronger,

with hydrogen lines appearing in emission with P Cygni profiles, while ionized iron dominated the spectrum (Mattei and Allen 1979). AAVSO light curves for this period show a disruption in the normally cyclic behavior of the luminosity associated with the light period of this star (387 days). Since 1934 the visual curve resembled that of an "ordinary" Mira variable with superposed forbidden emission lines.

From our analysis we attribute the brightening in 1934 to an eruption event or a "mild nova" in which the UV emission of the companion probably became comparable to the luminosity of the M7 star for a short time. This is consistent with Merrill's interpretation of a "simmering nova." The UV emission observed in our data and the forbidden line emission observed by Merrill (1950) and Ilovaisky and Spinrad (1966) is most likely the result of the excitation of a nebula by a bright white dwarf. Models postulating an O- or B-type main-sequence star as the excitation source of the nebula are ruled out by the continuum properties of the UV spectrum. Accordingly, our model is constrained to one in which a bright white dwarf ( $\sim \text{few } L_\odot$ ) is the companion to the M7 giant. The fact that a white dwarf is capable of supplying enough ionizing photons to excite the emission lines observed further strengthens this interpretation.

The possibility that R Aqr has been subject to eruptions in the past is suggested by earlier observations made by Hubble, who observed an expansion of the outer nebulosity that extends for  $2'$  around the central star. Baade (1942) confirmed Hubble's observations of expansion rates of  $80\text{--}100 \text{ km s}^{-1}$ . The velocities observed places the onset of expansion about 600 yr ago.

We can summarize the general properties of our model as follows: R Aqr is a symbiotic star system that most likely consists of an M7 primary and white dwarf companion. The 27 yr period adopted from Merrill (1950) for the companion star is such that for reasonable mass ratios of 1:1 and 2:1 (assuming the dwarf to be  $1 M_\odot$ ) the physical separation of the stars is a few times  $10^{14} \text{ cm}$ , which is also the approximate dimensions of the ionized nebula. The faint hot companion star is itself not sufficiently luminous to be observable directly. Its presence, however, is manifested by the ionizing effects that it has on its immediate surroundings, which creates a low-excitation nebula. Further observations in the radio, visible, and ultraviolet would be useful in monitoring the time dependence of the different emitting regions.

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