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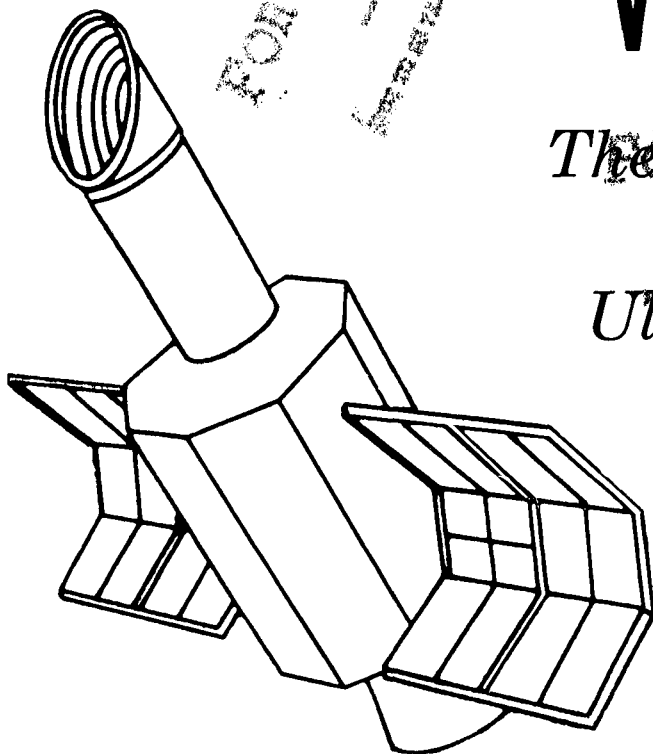
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IUE OBSERVATIONS OF CIRCUMSTELLAR EMISSION FROM THE LATE TYPE VARIABLE R AQR (M7 + pec)

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ABSTRACT

As part of a program to observe circumstellar emission from late type stars, IUE observations of R Aqr (M7 + pec) have been obtained in low dispersion. Strong permitted, semi-forbidden and forbidden emission lines are seen, superimposed on a bright ultraviolet continuum. 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 orbital radius of the binary system of which R Aqr is the primary star. The low excitation emission lines of Fe II, Mg II, O I and Si II probably arise in the chromosphere $(T \sim 10,000$ K) of the R Aqr. The secondary is probably 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 as to escape detection by direct observation. We attribute the UV continuum to Balmer recombination from the dense nebula and not to blackbody emission from the hot companion.

I. Data, Analysis, and Introduction

Ultraviolet spectra (Figures 1 and 2) of the late type star R Aqr (M7 + pec) have been obtained with the International Ultraviolet Explorer (IUE) and reveal intense emission lines and continuum. This is consistent with earlier optical observations of Merrill[1, 2, 3] which indicate that the system consists of hot stellar companion and a relatively cool late type star. In low dispersion the spectrum between 1200 Å to 3200 Å shows strong permitted emission lines of C IV (1548 Å, 1550 Å), Si III (1883 Å, 1892 Å), C III (1907 Å, 1909 Å) and Mg II (2796 Å, 2803 Å), forbidden emission lines of O II (2470 Å) and probably [O III] (2321 Å). The UV observations are thus consistent with lines of [O III] (4929 Å, 5007 Å) observed in the optical spectra of Merrill[3] and [O II] (3726 Å, 3729 Å) of Ilovaisky and Spinrad[4].

The strong lines of He II, C II, C IV , O I, O III , O IV, S II, Si IV and Fe II are evident in the spectrum. The identification of N V and Si II 1304 Å, 1309 Å is ambiguous 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.

In addition to the bright emission line spectrum there is a general ultraviolet continuum, the intensity of which appears independent of wavelength over the spectral range observed. We attribute the origin of this continuum to hydrogen recombination rather than H I two-photon emission.

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 main sequence star is the source of excitation in the nebula, as has been suggested by Merrill[3]. We conclude that the continuum observed most likely originates not from a stellar source, but from a low excitation nebula with an electron temperature $T \sim 15,000$ K and characteristic size 10^{15} cm. The source excitation is a sub-luminous 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.

The low excitation lines of Fe II and Mg II have been previously observed in the spectra of single late type stars by Carpenter and Wing [5], and the presence of the above lines as well as O I and Si II lines in the UV spectrum of R Aqr argues strongly for a cool chromosphere $T_* \sim 10,000$K for the primary M7 star[6]. However, we assume from our analysis that 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.

The observed continuum flux can 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 spectrum. For that purpose we have used the combined strengths of C II (2325, 2327, 2328 Å), C IV (1548, 1551 Å), C III] (1907, 1909 Å), [O II] (2470 Å), [O III] (2321 Å) and O IV] (1400, 1401, 1405, 1407 Å). We have selected these lines because they consist of various ion species, they are the strongest features in the spectrum, and because there is little ambiguity in identification. However, it is not clear if the 1402 Å feature is due entirely to O IV], and what portion of the broad 2328 Å feature is due to [O III] or C II.

The observed continuum is essentially flat and rises slightly toward long wavelengths. The continuum, therefore, cannot be due to a star since a stellar continuum would vary with wavelength by more than an order of magnitude over the spectral range observed. Balmer recombination and H I two-photon emission arising from a nebula are possible mechanisms to explain this continuum. However, shortward of 3200 Å the two-photon continuum of hydrogen will dominate if the densities are sufficiently low ($\lesssim 10^4$ cm^{-3}), and will produce a prominent peak in intensity around 1400 Å (Bohlin, Harrington and Stecker[7]); this peak is not observed in our data, 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 $T \sim 15,000$ K and the expected flux varies only by a factor of

two between 1200 to 3200 Å. We conclude that this mechanism dominates and that the densities involved must be $\gtrsim 10^5$ cm^{-3}, since densities appreciably lower than this value would result in a conspicuous two-photon continuum peak around 1400 Å. Given this lower limit in density we can calculate a corresponding upper limit for the diameter of an ionized nebula responsible for the observed flux, $\sim 5 \times 10^{14}$ cm.

A further argument in support of a nebula with this characteristic size and density as that found above can also be made from observations of emission lines in the visible by Merrill[3]. Merrill[3] determined an orbital period for the hot companion of approximately 27 years from radial velocity measurements. The corresponding size of the semi-major axis for an elliptical orbit with this period is 1.7×10^{14} to 2.1×10^{14} cm, for a mass ratio of the primary and secondary of 1:1 and 3:1, respectively (assuming one solar mass for the secondary). If the ionized nebula was appreciably larger than the separation of the stars one would not expect to observe substantial variations in line strengths. However, Ilovaisky and Spinrad[4] 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[3] also found that the apparent position of the nebular emission appears to vary with time. Accordingly, this is consistent with our model that suggests the ionized nebula is comparable in scale to the size of the binary orbit. At a distance of 260 pc a central ionized cloud of scale size $L = 2 \times 10^{14}$ and electron density of $n_e = 1.5 \times 10^7$ cm^{-3} is sufficient to explain the observed recombination continuum.

The densities we obtained above from observations of the UV continuum can also be roughly checked by the [O III] line strengths observed by Merrill[3] who found that the 4363 Å line is unusually strong, and that prior to 1934 "the ratio of its intensity of 4959 Å is equaled or exceeded in only one other nebula, IC 4997". The intensity of the hydrogen lines relative to those of [O III] R Aqr is similar to that observed in most planetary nebulae, Hβ being about equal to 4959 Å prior to 1922. After this time the hot component started to dominate the spectrum for a few years reaching a maximum in 1933-34[8]. From Aller and Liller[9] we estimate the intensity ratio of the 4363 Å to 5007 Å and 4959Å i.e. I(4363 Å)/I(4959 Å, 5007 Å) 0.1 for the planetary nebula IC 4997 observed in 1922. Based upon the observations of IC 4997 (Aller and Liller[9] and the statement of Merrill [3] concerning the similarity of this ratio of R Aqr to that of IC 4997 prior to 1934 (i.e. 1922), it follows that the strength of the 4363 A line agrees with densities $10^6 \lesssim n_e \lesssim 10^8$ cm^{-3} for temperatures $3 \times 10^4 \lesssim T \lesssim 8 \times 10^3$, respectively (Kafatos and Lynch[10].

Moreover, as deduced from our continuum measurements the nebular density cannot be more than $\sim 10^8$ cm^{-3} since the [O II] and O [III] lines would be suppressed, and the 4363 Å line would be even stronger. Additionally, if densities were much higher the nebula would be comparable in extent to the size of the primary M7 star, which is unrealistic on physical grounds. It follows that the nebular parameters from the foregoing arguments are in the

range $10^5 \lesssim n_e \lesssim 10^8$ cm^{-3}, $10^{14} \lesssim L \lesssim 10^{15}$ cm, and $10^4 \lesssim T \lesssim 3 \times 10^4$ K. We adopt a model $n_e \lesssim 10^7$ cm^{-3}, $L \sim 2 \times 10^{14}$ cm and $T \sim 15,000$ K.

b.) Emission Lines

We have also deduced the nebular parameters and the relative ionic abundances by two different methods, i) by using the carbon line strengths, ii) by using the oxygen line strengths. We have assumed that the scale size of the nebula is $L \sim 2 \times 10^{14}$ cm; although the general trend of our results appears somewhat insensitive to this parameter, we have assumed normal cosmic abundances for the various elements under consideration[11].

i) carbon line strengths (model A)

The semi-forbidden lines of C II and C III and the allowed lines of C IV can be used with one another to find the product $n^2 L^3$ [12, 13, 14, 15]. 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 (even if the [O III] were present it would not be more than 0.1 of the total intensity of the feature). The results of this calculation are shown in Table 1 (Model A). The ionic abundance 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). We can also obtain the ionic abundance of He III from the 1640 Å line using this carbon line strength analysis. However, the ionic abundance of the He III is found to be large in this case and all of the helium would have to be doubly ionized. We have deduced the H-α (6563 Å) and [O III] 5007 Å) as well as the flux of the continuum in Table 1 (Model A). Although Model A is not unique it does indicate a general trend in our data. Reasonable ionic abundances for the oxygen ions can be obtained if we use the carbon line strengths to $n^2 L^3$. However, the densities would have to be generally lower than might be suggested by the strong [O III] 4363 Å line observed by Merrill[3]. Additionally, the computed flux level of the continuum from Model A is too low to explain our data.

ii) oxygen line strengths

Assuming the 2328 A feature is mainly due to [O III] and the 1402 Å feature is mainly O IV], one can obtain values of n_e and T [10]. Since collisional depopulation becomes important above 10^6 cm^{-3}, the 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 (Case 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 abundances of carbon in this analysis, the line strengths should be a factor of ~50 larger than what is observed. The only alternative is to assume that atomic carbon is under-

abundant by a factor ~ 50 in the ionized nebula. The depletion of carbon could be the result of the precipitation of carbon into grains. The relatively low abundance deduced in our analysis appears generally to be the case since this result will not change even if parameters in Table 1 are varied (say the temperature is varied between 10,000 K to 15,000 K). At this point, however, it is not possible to distinguish between either Models A or B. It suffices here to say that Model B appears more attractive since it does account for the continuum.

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, $n_e \sim 10^5 - 10^7$ cm^{-3} and $T \sim 15,000$ K agree with the general parameters for nebular emission in symbiotic stars of[16].

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 of the M7 giant to be 24 km s^{-1}, that was obtained using the period-density relation for a period = 387 days and an assumed stellar mass of 1$M_\odot$ to 3$M_\odot$, we find $\dot{M} = 10^{-7} M_\odot$yr^{-1} for a nebula of radius $r \equiv L/2$ 10^{14} cm and density $n_e \sim 1.3 \times 10^7$ cm^{-3}. This mass loss rate is probably a lower limit since, as will be shown later on, 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 a nebula. However, since we have assumed that the source of nebular excitation is a sub-luminous white dwarf, the nebular continuum flux observed of 10^{-13} ergs cm^{-2} s^{-1} A^{-1} places an upper limit of flux that is contributed by the companion. In Table 2 we show the stellar parameters for the unseen companion if its flux contribution in the continuum is this upper limit.

In the first column of Table 2 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} A^{-1} at 1200 Å. The third column gives the luminosity in solar units. Columns 4 and 6 give the absolute flux and 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 $m_v \sim 8$ magnitudes. In order for it to be observable today the continuum would have to be 10^4 times greater. The 1934 event appears, therefore, to have been en 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.

359

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 1.5×10^5 K, although temperatures as low as 5×10^4 K could be assumed if the density of the nebula was slightly lower than that shown in Model B. It is most likely the case that the compact ionized nebula is "ionization" bound rather than "density" bound and therefore, the mass rate for the primary of 10^{-7} $M_\odot$ yr^{-1} is likely a lower limit. We also find that nebular temperatures greater than 15,000 K are required, 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, $n_e \sim 10^7$ cm^{-3}, $1.5 \times 10^4 \leqslant T \leqslant 2.5 \times 10^{14}$ cm, and the companion $5 \times 10^4 \leqslant T \leqslant 1.5 \times 10^5$ K, $0.7 \leqslant L_* \leqslant 7L$ can account for the nebular continuum, explain the observed emission lines, and provide sufficiently low stellar luminosity that the companion could not be seen directly.

III. Summary

The UV emission observed in our data and the forbidden line emission observed by Merrill[3] and Ilovaisky and Spinrad[4] are most likely the result of the excitation of a nebula by a white dwarf. If an O or B type main sequence star is postulated as the excitation source of the nebula, such a model could not reconcile the continuum properties of the ultraviolet spectrum. Accordingly, our model is constrained to adopt a model in which a bright white dwarf (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. 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 year period we have adopted from Merrill[3] for the companion star is such that for reasonable mass ratios of 1:1 and 1:2 (assuming the dwarf to be a $1M_\odot$) the physical separation of the stars is a few $\times 10^{14}$ 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 in the ionizing effects which it has on its immediate surroundings, which create a low excitation nebula. Further observations in the radio, visible and ultra-violet would be useful in monitoring the time-dependence of the different emitting regions.

REFERENCES

1. Merrill, P.W., 1921, Astrophys. J., 53, 375.
2. _____. 1935, ibid, 81, 312.
3. _____. 1950, ibid, 112, 514
4. Ilovaisky, S.A. and Spinrad, H. 1966, Pub. Ast. Soc. Pacific, 78, 527.
5. Carpenter, K.G. and Wing, R.F. 1979, Bull. Am Ast. Soc., 11, 419.
6. Linsky, J.L. 1979, Bull. Am. Phys. Soc., 24, 771.

7. Bohlin, R.C., Harrington, J.P. and Stecker, T.P., 1978, Astrophys. J.,
    212, 575.
8. Mattei, J.A. 1979, J. Roy. Ast. Soc. Canada, in print.
9. Aller, L.H. and Liller, W. 1966, M.N.R.A.S., 132, 337.
10. Kafatos, M. and Lynch, J.P. 1979, Astrophys. J., submitted.
11. Cameron, A.G.W. 1973, Space Sci. Rev., 15, 121.
12. Osterbrock, D.E. 1963, Pla. Space Sci., 11, 621.
13. _____. 1970, Astrophys. J. 160, 25.
14. _____. 1974, Astrophysics of Gaseous Nebulae (W.H. Freeman
    & Co., San Francisco).
15. Bely, O. 1966, Proc. Phys. Soc., 88, 587.
16. Boyarchuck, A.A. 1975, Variable Stars and Stellar Evolution, eds.
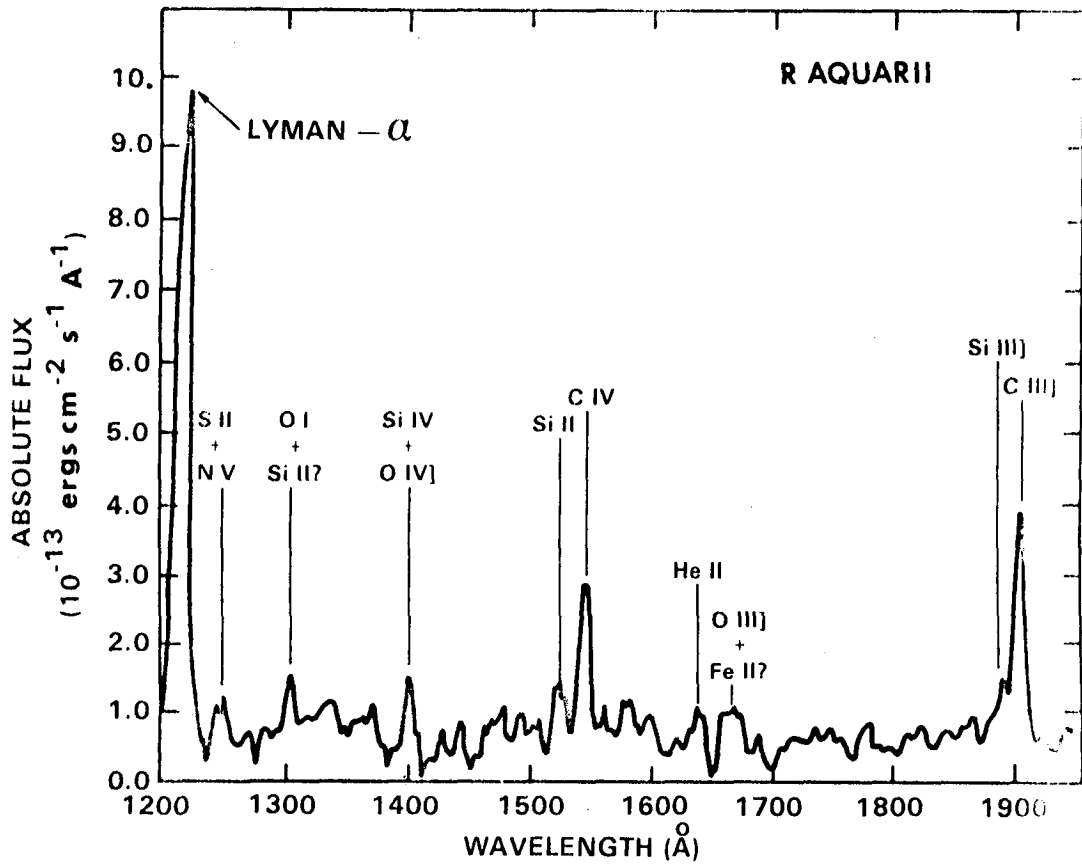   Sherwood, V.E. and Plaut, L. (D. Reidel Pub. Co.-Holland), 377.

Figure 1:
Low dispersion (~ 6 A resolution) spectrum of R Aqr obtained on
July 25, 1979 in the wavelength range 1200 Å to 2000 Å using the large.
aperture (10" x 20") of the IUE spectrometer. The exposure time on the
SEC Vidicon camera was 10 minutes. The Lyman-α line at 1216 Å has a
combined intensity of the geocoronal and stellar
Lyman-α emission. The spectrum is deconvolved and geometrically and
photoelectrically corrected. The absolute flux scale is accurate to a
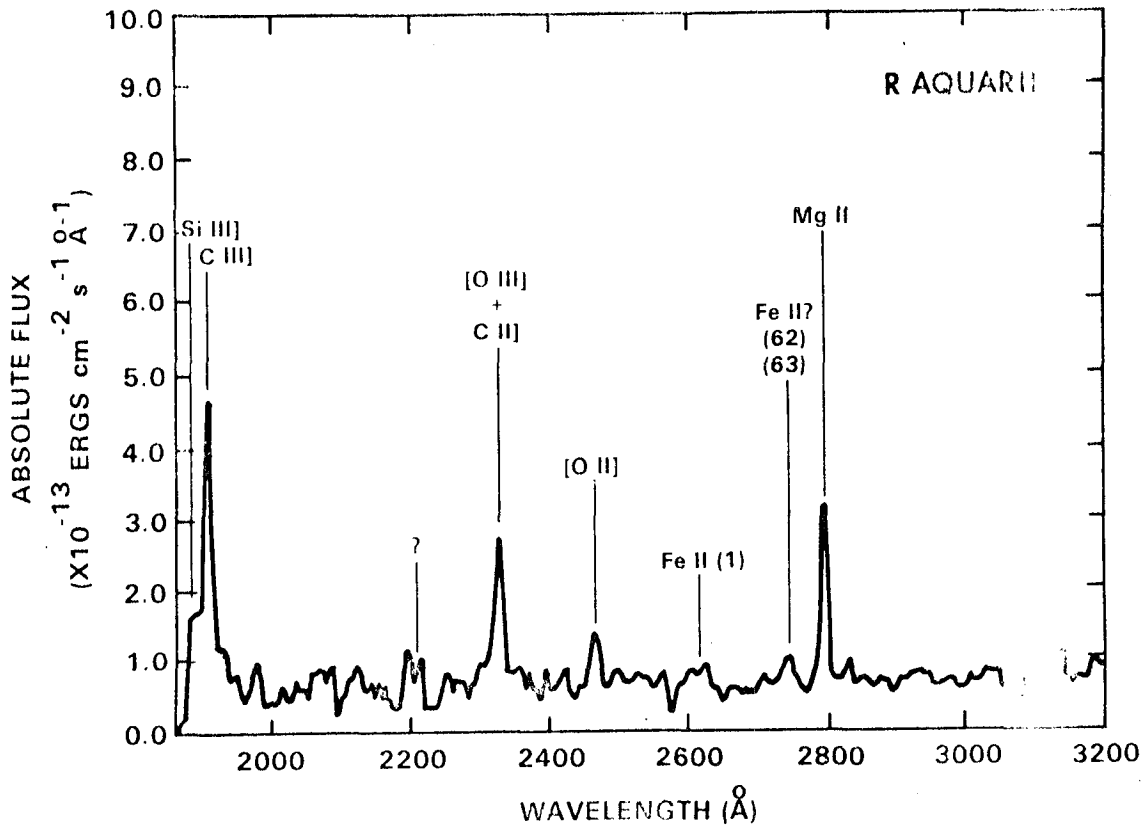factor two using the standard IUE reduction program.

Figure 2:
Low dispersion spectrum of R Aqr between 2000 Å and 3200 Å 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.

TABLE 1

Nebular Parameters

$$L = 2 \times 10^{14} \text{ cm}, \quad T = 15{,}000K$$

Case A Carbon Line Analysis		Case B Oxygen Line Analysis	
$n_e^2 L^3 (\text{cm}^{-3})$	4.4×10^{55}	$n_e^2 L^3 (\text{cm}^{-3})$	1.25×10^{57}
N(C II)	0.53	N(O II)	0.06
N(C III)	0.32	N(O III)	0.86
N(C IV)	0.15	N(O IV)	0.08
$n_e (\text{cm}^{-3})$	2.3×10^6	$n_e (\text{cm}^{-3})$	1.25×10^7
N(O II)	0.81	N(C II)[*]	0.09
N(O III)	0.19	N(C III)[*]	0.55
N(He III)	1	N(C IV)[*]	0.36
Flux (H-α) 6563A (ergs cm^{-2} s^{-1})	1.2×10^{-12}	N(He III)	0.02
Flux [O III] 5007A (ergs cm^{-2} s^{-1})	1.5×10^{-12}	Flux (H-α) (ergs cm^{-2} s^{-1})	3.3×10^{-11}
$F_{Continuum}$(2000A) (ergs cm^{-2} s^{-1} A^{-1})	10^{-15}	Flux [O III] 5007A (ergs cm^{-2} s^{-1})	5.5×10^{-11}
		$F_{Continuum}$(2000A) (ergs cm^{-2} s^{-1})	2.0×10^{-14}

[*]see discussion in text

TABLE 2
HOT COMPANION

$T_*(K)$	$R_*/R_\odot$	$L_*/L_\odot$	M_V	m_V	$N_i(s^{-1})$
1.5×10^5	4.1×10^{-3}	7.4	12	19.1	4.3×10^{44}
10^5	5.6×10^{-3}	2.8	11.4	18.5	2.0×10^{44}
5.0×10^4	1.2×10^{-2}	0.75	10.1	17.2	5.0×10^{43}

T_* : stellar temperature

R_* : stellar radius

L_* : stellar luminosity

M_V : absoulte visual magnitude

m_V : apparent visual magnitude

N_i : number of ionizing photons emitted by companion