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INTERNATIONAL ULTRAVIOLET EXPLORER OBSERVATIONS OF THE R AQUARII JET

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ABSTRACT

Ultraviolet spectra were obtained with the *International Ultraviolet Explorer* of the newly discovered optical-radio jet feature in the symbiotic variable R Aquarii. The far-UV continuum of the jet is characterized by strong continuum which rises with decreasing wavelength in the 1200–2000 Å wavelength range and is considerably different in appearance from the relatively flat continuum exhibited by ionized nebulosity in the central star. Prominent Si III] and Si II emission lines seen in the central region are virtually absent in the jet. This could reflect the depletion of silicon in the feature, the result of grain formation in material that has been ejected by the central star. Consistent with this interpretation is the overall excitation of the jet that suggests it is cooler than the nebulosity that engulfs the central UV object.

Subject headings: stars: circumstellar shells — stars: long-period variables — ultraviolet: spectra

I. INTRODUCTION

Observations of the recently discovered jet feature in the symbiotic variable R Aquarii (M7e + pec) have been obtained with the *International Ultraviolet Explorer* (*IUE*). A comparison of low-dispersion UV spectra (about 6 Å resolution) reveals important differences in the wavelength distribution of continuum energy between the central ionized nebula and jet feature. The UV continuum flux, F_λ, between 1200–2000 Å that rises with decreasing wavelength in the jet feature is essentially independent with wavelength in the central star. Additionally, the prominent emission lines of Si III] λ1892A and Si II λ1817, evident in the central star, are virtually absent in the jet. The carbon lines of C IV, C III], and C II also suggest the general excitation of the jet is comparatively lower than that of the central star. This is further indicated by enhanced S II λλ1250, 1295 and C II λ1335 emission in the feature. We speculate that material that is ejected from the symbiotic system cools through free-free and nebular recombination emission.

The jet or "spike," so-called by Wallerstein and Greenstein (1980), first appeared sometime between 1970 and 1977. Herbig (1980) reported, from optical spectra, moderate ion excitation in the jet that consists of [S II], [O II], [O III], and He I. Subsequent observations obtained with the Very Large Array (VLA) indicate the feature is also present at 6 cm and 1.3 cm (Sopka *et al.* 1982). The relationship between the jet and the outer, extended 2′ nebulosity is not clear at present. However, Lick Observatory 3 m direct plates obtained by Herbig (1980) indicate material is ejected along an axis perpendicular to the 2′ nebulosity that encircles the central object. Kafatos and Michalitsianos (1982) have suggested this is possibly the result of tidal interaction between a hot subdwarf and the 387 day period Mira variable that was near maximum light during our *IUE* observations (*IUE* FES monitor = 6.5 mag). Morphologically, the feature possibly resembles low-velocity (100 km s^{-1}) discrete blobs of ejecta reported in Herbig-Haro objects (Herbig and Jones 1981) and in the planetary nebula Abell 30 (Hazard *et al.* 1981).

II. OBSERVATIONS

IUE instrumentation is described by Boggess *et al.* (1978). The spatial extent of the 10″ feature and roll-angle of the spacecraft on 1982 May 7 enabled us to eliminate most of the contribution from the central UV star. In Figure 1, the VLA 6 cm map obtained by Sopka *et al.* (1982) on 1981 November 5 is shown, on which is superposed the position of the *IUE* large and small entrance apertures. At slit position (*a*), spectra of the jet were obtained at an aperture-centered distance ~ 10″ from the central star. At position (*c*), the slit was positioned to obtain an estimate of instrument-scattered light from the central UV source. Finally, the central UV star (position (*b*)] was observed in both the large and small (3″ hole) apertures for comparison with the

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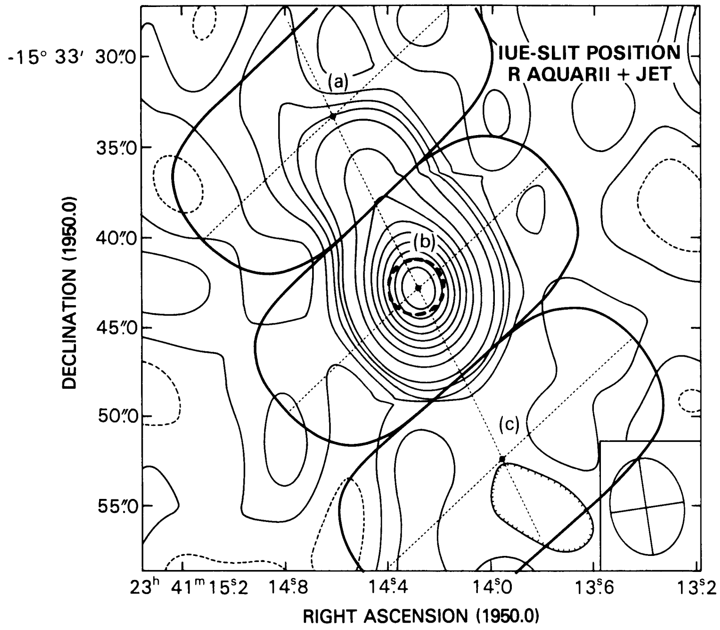

FIG. 1.—*IUE* entrance aperture shown on the VLA 6 cm map obtained by Sopka *et al.* (1982). The long axis of the large 10″ × 20″ aperture of *IUE* and the axis defined by the protruding jet feature and central star are shown by dashed lines. Position (a) is centered 10″ from the jet feature.

TABLE 1

IUE OBSERVING PROGRAM

IUE Camera and Image No.	Entrance Slit (arcsec)	Position[a, b]	Exposure (minutes)
SWP 16916......	10 × 20	(a)	240
LWR 13188	10 × 20	(a)	40
SWP 16917......	10 × 20	(c)	60
SWP 16918......	10 × 20	(b)	30
LWR 13189	10 × 20	(b)	20
SWP 16919......	3 hole	(b)	30

[a] See Figure 1.

[b] (a): R Aqr Jet; (b): central star; (c): UV scattered light.

jet (Table 1). *IUE* spectra were reduced with the corrected ITF of Cassatella *et al.* (1980) adopted for *IUE* spectra.

Notable differences in emission-line structure between spectra of Figure 2 include the apparent weakness of Si III] λ1892 and Si II λ1817 emission in the jet. If the level of silicon emission in the jet is due entirely to instrument-scattered light from the central UV source, we estimate the scattered light contribution by the central star is around 2%. Additionally, C IV λλ1548, 1550 and C III] λ1909 were detected at slit position (*c*). The intensity ratio of these emission lines appears reversed from that found in either the jet or central star, i.e., $I(\text{C IV})/I(\text{C III]}) \geq 1$, and is not satisfactorily explained by instrument-scattered light. We suspect, therefore, we are possibly encountering nebular emission at position (*c*) that differs in thermal excitation or composition, or both, from either the jet or central star material. Is a counterjet possibly forming?

III. DISCUSSION AND CONCLUSIONS

The UV continuum in the jet rises steadily with decreasing wavelength over the 1200–2000 Å wavelength range. The jet continuum, however, cannot extend to the X-ray energy range (1–4 keV), where the extrapolated UV flux would suggest X-ray emission three orders of magnitude above the threshold obtained by Helfand (private communication) of $\sim 3 \times 10^{-13}$ ergs cm^{-2} s^{-1} Å^{-1} with the Image Proportional Counter (IPC) on the *Einstein Observatory* (*HEAO-B*). His data indicate R Aquarii is not a soft X-ray source.

Assuming negligible extinction in the jet feature, we find $F_\lambda \propto \lambda^{-n}$ where $n = 2.5 \mp 0.5$ in the short-wavelength range. A flatter spectrum (with say $n = 1.5$) underestimates the level of the observed continuum in the jet below ~ 1300 Å. If we adopt an $E_{B-V} = 0.65$ found in the central nebulosity (Kaler 1981; Wallerstein and Greenstein 1980) for the feature, the continuum rises very rapidly below 1400 Å. A value $E_{B-V} = 0.0$ seems more appropriate for the jet, is within the extreme range of values suggested by Wallerstein and Greenstein (1980), i.e., $E_{B-V} = 0.0$–0.5, and will be used herein. We note that similar UV continuum properties have been observed in the Herbig-Haro objects by Brugel,

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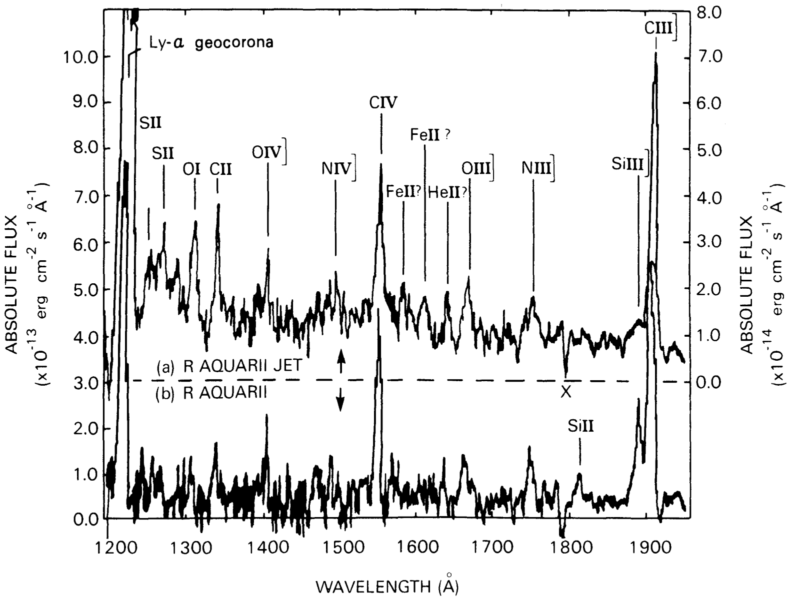

FIG. 2.—Short-wavelength spectra [SWP 16916: position (a), and SWP 16918: position (b)] are shown for the jet and central object. Note the top spectrum for the jet (*right-hand scale*) is plotted in different absolute flux units than for the central star (*left-hand scale*). The spectra shown are not corrected for reddening.

Bohm, and Mannery (1981) for $n \sim 2$–3. They attribute the observed UV continua to dust-scattered stellar continua from hot stars present in these objects. Taking an emission measure, $n_e^2 L^3 = 4.3 \times 10^{55}$ cm^{-3}, appropriate for $T_e = 10^4$ K in the jet (obtained below), we find that the computed recombination and free-free continua at 1900 Å is $\sim 10^{-15}$ ergs cm^{-2} s^{-1} Å^{-1}, a factor of ~ 0.1 of the observed continuum level. If lower temperatures in the jet are considered, free-free and recombination emission could account for the continuum longward of 2000 Å. However, the wavelength distribution of UV continuum below 1900 Å is not satisfactorily explained by nebular continuum emission alone. Dust scattering of stellar ultraviolet continuum similar to that suggested for Herbig-Haro objects by Brugel *et al.* might be applicable here.

The absolute emission-line fluxes shown in Table 2 for the central region agree closely with those obtained previously by Michalitsianos, Kafatos, and Hobbs (1980). The only exception is Si III] λ1892, which is found here a factor of ~ 3 greater, and [O II] λ2470 which decreased by a factor of ~ 2. In general, emission-line fluxes are 4–10 times greater in the central star compared with the jet. The continuum is ~ 5 times weaker than the central star, but at wavelengths $\lambda \leq 1400$ Å is only ~ 2.5 times less intense. We have carried out the UV line analyses in a fashion similar to that of Michalitsianos *et al.* For the carbon lines, we assume that the [O III] contribution at λ2328 C II] feature is negligible (cf. Johnson 1982), and assume that $N(\text{C II}) + N(\text{C III}) + N(\text{C IV}) = 1$, where N denotes the relative ionic abundance. We find that the nebular parameters in the jet are $T_e(\text{jet}) \sim 10^4$ K and $n_e^2(\text{jet}) L^3(\text{jet}) \sim 4.3 \times 10^{55}$ cm^{-3} for $E_{B-V} = 0.0$.

Based on previous analysis (cf. Michalitsianos, Kafatos, and Hobbs 1980), the comparatively flat continuum observed in the central star is probably nebular. Assuming that the He I λ2945 line arises in the same region as the carbon lines, we find that a consistent analysis is not possible for $T_e = 1.5 \times 10^4$ K unless $E_{B-V} \geq 0$ is assumed for the denser central nebulosity. However, for lower temperatures, say $T_e = 10^4$ K, one could accommodate an $E_{B-V} = 0.0$ and be consistent with the observed line intensity ratios. There is no unique way to obtain nebular parameters for the central object given the uncertainties in E_{B-V} discussed earlier. We prefer high electron temperatures in the central nebulosity $T_e(*) \sim 1.5 \times 10^4$ K compared with $T_e(\text{jet}) \sim 10^4$ K. The central nebula emission measure then is $n_e^2(*) L^3(*) \sim 4.3 \times 10^{57}$ cm^{-3}, if a normal galactic law for $E_{B-V} = 0.65$ applies, and agrees with the strength of Hα λ6563 observed by Wallerstein and Greenstein (1980). For a size $L \sim 2 \times 10^{14}$ cm of the central nebulosity (Kafatos and Michalitsianos 1982), we find that $n_e(*) \sim 2.3 \times 10^7$ cm^{-3}, which is appreciably higher than $n_e(*) \sim 1.5 \times 10^6$–$4 \times 10^6$ cm^{-3} obtained by Wallerstein and Greenstein (1980) in the visible from the [O III] line strengths. If the size of the line-emitting region around the central star and jet is similar, we find that $n_e(*)/n_e(\text{jet}) \sim 10$. The prevailing electron densities $\leq 10^9$ cm^{-3} in the central ionized region and jet suggest that the line intensity ratio of Si III] λ1892 and

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TABLE 2

PROMINENT EMISSION LINES

TRANSITION	λ(Å) LABORATORY	SLIT POSITION (a)		SLIT POSITION (b)	
		λ(Å) *IUE*[a]	Absolute Flux[b]	λ(Å) *IUE*	Absolute Flux[b]
N v?	1238.8, 1242.8	...	...	1241.2	0.258
S ii	1250.5	1251.1	0.034	1254.4	0.309
S ii	1259.5	1265.1	0.063	1265.8	0.238
O i	1304.9, 1306.0	1305.9	0.226	1305.0	0.487
C ii	1334.5, 1335.7	1336.5	0.179	1336.4	0.641
O iv	1399.8, 1401.1 1404.8, 1407.4	1403.1	0.079	1403.8[c]	0.729
?	?	1466.0	0.051	1469.4	1.220
N iv]	1486.5	1484.7	0.056	1488.6	0.591
C iv	1548.2, 1550.8	1549.9	0.240	1549.4	3.569
Fe ii?	1559.1, 1588.3 mul. (44), (45)	1580.7	0.091	...	...
Fe ii?	1608.5–1640.0 mul. (43), (8)	1608.5	0.074	...	...
He ii?	1640.3	1638.7	0.074	1636.0	0.723
O iii]	1660.8, 1661.1	1667.1	0.178	1664.0	1.053
N iii]	1748.6, 1749.7 1752.2, 1754.0	1751.3	0.097	1751.2	1.505
Si ii	1808., 1816.9	...	...	1814.4	0.384
Si iii]	1892.	1892.1	0.015	1891.8	0.815
C iii]	1908.7	1908.9	0.648	1908.6	2.448
[O iii] + C ii]	2321.7, 2325.1 2326.9, 2328.1	2333.0	0.523	2328.4	2.410
[O ii]	2470.4	2470.6	0.229	2471.2	0.880
Fe ii	2599.4 − 2631.3 mul. (1)	...	...	2617.0	1.809
Fe ii	2739.5 − 2755.7 mul. (62), (63)			2750.6	0.850
Mg ii(*h* and *k*)	2795.5, 2802.7	2801.8	0.650	2799.4	4.380
He i + C ii + O iii?	2829.1 + 2836.7 2837.6 + 2837.2	...	...	2836.0	0.482
He i	2945.1	...	...	2945.5	0.297

[a] Corrected $\Delta\lambda = +4.3$ Å instrumental blueshift.

[b] Flux values ($\times 10^{-12}$ ergs cm^{-2} s^{-1}) uncorrected for extinction.

[c] Possible blend Si iv + O iv].

C iii] λ1909 is not greatly affected by moderate variations in electron density (P. Dufton, private communication).

If relatively cooler temperatures prevail in the jet, a substantial fraction of available silicon might become involved in grain or silicate dust formation. Comparably lower temperatures in the feature indicated by enhanced emission from S ii, O i, and C ii would promote the formation of grains and explain weak silicon. It is interesting to speculate that silicates formed under these conditions possibly do not selectively absorb at 2200 Å and that this explains the anomalous UV extinction properties of R Aquarii (cf. Johnson 1982). We have used calculations of Nussbaumer (1982) to analyze the line intensities of Si iii] and C iii] in order to obtain abundances. The C iii] λ1909 line was selected because it corresponds closely in wavelength to the Si iii] line, minimizing extinction effects if important. From the absolute flux measured for these lines, we find that $n(\mathrm{C})/n(\mathrm{Si}) \sim 2.8$ for position (b), while $n(\mathrm{C})/n(\mathrm{Si}) \sim 88$ at position (a), where $n(\mathrm{C})$ and $n(\mathrm{Si})$ denote element number densities. While charge transfer (not considered by Nussbaumer 1982) may influence our analysis, we obtain

$$\left.\frac{n(\mathrm{C})}{n(\mathrm{Si})}\right|_{\mathrm{jet}} \Big/ \left.\frac{n(\mathrm{C})}{n(\mathrm{Si})}\right|_{*} \sim 30.$$

As such, the UV spectrum of the jet is reminiscent of planetary nebulae spectra, which, in a number of cases, indicate silicon depletion (cf. Harrington and Marionni 1980).

In conclusion, *IUE* observations of the newly discovered jet in R Aquarii suggest the feature is comparatively less dense and probably cooler than the nebulosity that engulfs the central object. The UV continuum exhibits an energy distribution different from the central nebula, that could be the result of dust-scattered stellar continuum from the central ionizing source, similar to

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that suggested for Herbig-Haro objects. Silicon may be depleted in the jet feature, although the prevailing lower temperatures could promote the formation of silicates.

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