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EVIDENCE SIGNALING THE START OF ENHANCED COUNTERJET FLOW IN THE SYMBIOTIC SYSTEM R AQUARII

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ABSTRACT

The velocity structure of strong far-UV emission lines observed in the symbiotic variable R Aqr suggests the start of *new* jet activity which will probably culminate in the appearance of a series of intense nebular emission knots within a decade. This is indicated by a systematic redward wavelength drift of emission lines, which we have followed with the *International Ultraviolet Explorer* (*IUE*) since the discovery of the brilliant northeast jet emission knots more than 10 years ago. The C IV λλ1548, 1550 resonance lines, which previously showed a prominent blue asymmetric wing that extended to velocities in excess −200 km s^{-1}, exhibit red wing asymmetry that extends to speeds of ∼ +200 km s^{-1} in late 1992. The C IV line profile structure is consistent with the model proposed by Solf (1993), who explains the appearance of the northeast jet knots in terms of a ∼300–500 km s^{-1} collimated wind that collides with slower moving material expelled earlier in a nova outburst that occurred ∼190 yr ago. Based upon these high-resolution UV spectra, similar emission structures should appear southwest of the central star when the counterwind (or stream) interacts with material in the southwest inner nebula. The apparent change in direction of flow could result from a precessing accretion disk that alters the projection angle of collimated flow from the disk poles. The direction of the collimated wind may be related to the binary orbit, because the velocity shifts associated with emission lines formed in the flow change direction on a timescale which is comparable to the binary period.

Subject headings: binaries: symbiotic — circumstellar matter — stars: individual (R Aquarii) — stars: mass loss

1. INTRODUCTION

R Aqr (M7e+pec) is a symbiotic variable which is surrounded by a extended filamentary nebulosity. Solf & Ulrich (1985) proposed the filamentary structure formed as a result of two distinct nova-like outbursts, in which the ∼90″ meniscus-shaped *outer nebula*—oriented east–west—is the remnant of an outburst that occurred ∼650 yr ago, while the north–south oriented bipolar *northeast–southwest inner nebula* was ejected in a more recent outburst ∼190 yr ago. The nebulosity surrounds a 387 day period Mira, accreting hot dwarf, and suspected accretion disk (see review by Michalitsianos & Kafatos 1988).

The appearance of a *brilliant* optical emission spike or jet more than a decade ago (Herbig 1980; Sopka et al. 1982) generated considerable interest in this system. Following its discovery in the optical the R Aqr jet was subsequently resolved at microwave wavelengths into a series of thermal emitting knots (Spergel, Guiliani, & Knapp 1983; Hollis et al. 1985) that define a broad arc which is ≥7″, in northeast extent. All of the optical, radio, and UV emission knots that comprise the R Aqr jet (Fig. 1: features A, B, C2, D) are embedded in the northeast inner nebula arm. The central H II region that surrounds the unresolved binary corresponds to feature C1. Feature A' at a position angle (PA) = 225° is probably a remnant of the nova outburst that formed the inner nebula southwest arm about 190 yr ago.

High spatial resolution [O III] λ5007 and [O II] λ3727 images obtained of R Aqr with the *Hubble Space Telescope* (*HST*) Faint Object Camera (FOC) (Paresce et al. 1991) suggest a continuous filamentary structure which extends northeast of R Aqr. Beyond ∼3″–4″ the structure becomes discontinuous, as if colliding with one of the optical/radio/UV emission jet knots (feature A). Solf (1993) interprets this morphology as a collimated supersonic ∼300–500 km s^{-1} wind, which forms shocks when the flow interacts with slower moving condensations associated with the expanding northeast inner nebula arm or jet parcels.

The presence of N V and He II emission in the northeast knots is consistent with shock-heated material, in which ionization temperatures of $T \geq 60{,}000$ K and densities of $n_e \leq 10^4$ cm^{-3}, respectively, are indicated in features A, B, D (see Michalitsianos & Kafatos 1988). Lower ionization and higher nebular densities prevail in feature C1 because of the absence of N V and He II, where permitted emissions of C II λλ1334, 1335, C IV λλ1548, 1550, and intersystem emission of N III] λ1750, Si III] λ1892, and C III] λλ1907, 1909 indicate $T_e \sim$ 15,000 K and $n_e \geq 10^6$ cm^{-3}.

We have obtained several high-resolution (HIRES) *IUE* echelle spectra of the central H II region (C1) and northeast jet

[1] *IUE* Guest Observer.

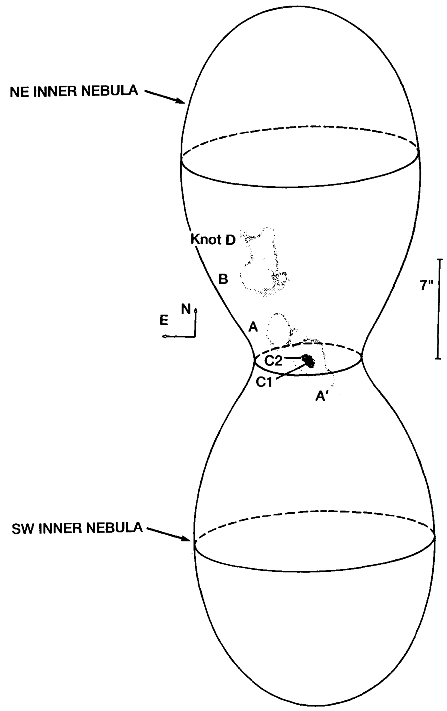

FIG. 1.—Schematic diagram of the northeast optical/radio/UV emission knots (features C2, A, B, D) that comprise the northeast jet extend ~7″, from the central unresolved binary and compact H II region (feature C1). The jet knots are embedded in the expanding northeast inner nebula (Solf 1993). The extended structure (feature A′) corresponds to slow moving material in the southwest inner nebula expelled in a nova-like outburst ~190 yr ago.

(features B + D) that support this interpretation. The C IV line profile structure on 1987 June 4 (epoch 1987.42) in the central H II region exhibited a broad asymmetric wing (FWHM ~ 200–300 km s^{-1}) which extended blueward to velocities ≥ −200 km s^{-1}. A relatively narrow emission component (FWHM ~ 100 km s^{-1}) is centered at the systemic velocity (V_r = −25 km s^{-1}; Hollis et al. 1986, 1990). A comparison of this structure with C IV line profiles obtained in 1992 December 25 (epoch 1992.99) indicates significant evolution has occurred during the 5 years that separate these observations. The C IV doublet now shows a prominent red wing that extends to velocities ~ +200 km s^{-1}.

We interpret the reversal of C IV wing asymmetry as evidence of a counterwind that is presently directed along the southwest inner nebula. The strongest emission lines detectable with *IUE*, i.e., C II, C IV, Si III], and C III], also indicate a redshift. A comparison of Si III] emission from our recent spectra with an *IUE* archive spectrum obtained in 1980 November 7 (epoch 1980.85) indicates the line radial velocity centroid has been drifting toward the red for more than a decade, i.e., since the time the northeast jet was first detected in 1980.86 (Herbig 1980). If interaction between the slower moving material and the counterwind occurs, as Solf (1993) suggests, explains the northeast jet emission knots, we can expect similar activity in the southwest inner nebula within, perhaps, a decade. The flow direction may be dependent on the binary orbit phase. This follows because the ~1 decade over which a systematic change in velocity centroids has occurred is roughly one-quarter to one-half of the estimated binary period, i.e., 27 and 44 yr. This supports models involving a precessing accretion disk in which the direction of flow from the disk poles is determined by the orientation of the disk relative to the Mira in this system (see Michalitsianos et al. 1988b; Kafatos, Michalitsianos, & Hollis 1986).

2. OBSERVATIONS

HIRES spectra SWP λλ1200–2000 (limiting resolution Δλ = 0.1–0.2 Å or ~ ±10–20 km s^{-1}) were obtained on 1987.42 (SWP 31102; 770 minute exposure) and 1992.99 (SWP 46585; 395 minute exposure). The SWP exposures were sufficiently long to obtain good signal-to-noise ratio in the C II, C IV, Si III], and C III] emission lines, but the adjacent UV continuum is underexposed. C III] λ1908.8 is saturated in all cases by a factor ≥1.5, making the absolute flux and velocity centroids for λ1908.8 unreliable. An additional 240 minute HIRES exposure (SWP 10558) obtained on 1980.85 was retrieved from the *IUE* archive and reprocessed. Si III] in SWP 10558 is strong and C III] λ1908.8 is saturated, while C IV, O I λ1300, and C II λλ1334, 1335 are very underexposed.

Target centering in the *IUE* 10″ × 20″ entrance aperture is critical for determining the correct wavelength scale. Pointing was verified by determining the relative position of guide stars in the *IUE* Fine Error Sensor (FES). The errors in pointing accuracy were 2–3 FES units (0″.25/FES units), which correspond to a velocity uncertainty of ~ ±10 km s^{-1}. We exercised care when applying spacecraft orbital elements to the datasets for IUESIPS processing; maximum errors are less than ±4 km s^{-1}. The heliocentric correction for each observing epoch was verified. The head amplifier temperature corrections (THDA) for the SWP camera differ by only a few degrees from the *reference ITF* temperature (8.5 C). The IUESIPS software properly accounts for linear shifts from this value. This correction is ≤2–3 pixels or ±10–20 km s^{-1}. In order to check for abnormal reseau motion due to image distortion, a close inspection of the Lyα geocoronal line was made. The wings of the Lyα line align well within the uncertainties (considering the different epoch of observations), indicating proper registration of the wavelength scale in the extracted spectra.

3. DISCUSSION

In Figure 2, the Si III] λ1892 line profiles are shown on a common velocity scale using a 5-point running average and correcting for the systemic motion V_r. The line profile suggests two-component structure. The narrow line profile exhibited a FWHM ~60 km s^{-1} on 1980.85 which was superposed on a blue asymmetric emission wing. The velocity width of the narrow line component increased to FWHM ~90 km s^{-1} on 1992.99, while a broad symmetric component is centered at the system velocity. The Si III] line profiles between 1980.85 and 1992.99 indicate a systematic drift toward larger (or redder) positive velocities. Other emission lines exhibiting similar red velocity centroid shifts are given in Table 1. The overall shifts of the centroids between 1980 and 1992 range from ~35 to 60 km s^{-1}. There seems to be no systematic correlation with degree of ionization of the parent species.

Wavelength displacement are also indicated in the C IV resonance doublet when comparing the doublet profiles on 1992.99 (Fig. 2, *top panel*) and 1987.42 (Fig. 3, *middle panel*) on a common velocity scale. C IV was extremely underexposed on SWP 10558 and is not shown.

The full base width of the C IV emission wing is ~350 km s^{-1} on 1987.42 (Fig. 3, *middle panel*). The blue asymmetric emission wing includes a prominent absorption feature at ~ −106 km s^{-1}, which is absent in 1992.99 (Fig. 3, *top panel*).

TABLE 1

R Aquarii Central H II Region Velocity Centroids and Absolute Fluxes for Strongest Emission Lines

Ion	λ(Å)Lab	SWP 10558 1980 NOV 7		SWP 31102 1987 JUNE 4		SWP 46585 1992 DEC 25	
		Flux[a]	$v_{\rm CENTROID}$(km s^{-1})[b]	Flux[a]	$v_{\rm CENTROID}$(km s^{-1})[b]	Flux[a]	$v_{\rm CENTROID}$(km s^{-1})[b]
C II	(1) 1334.53	0.9	−15	2.3	+15	1.3	+47
C II	(1) 1335.54	3.0	−14	2.6	−6	5.7	+37
C IV	1548.20	Weak?	...	20.0	+6	13.0	+33
C IV	1550.77	Weak?	...	31.0	+7	16.0	+12
O III]	1660.82	1.3	−43	2.6[c]	−11	2.1[e]	+12
O III]	1666.14	2.7	−30	9.6[d]	−2	6.8[e]	+21
Si III]	1892.03	8.2	−19	8.2	−1	9.3	+15
C III]	1906.73	6.2	−46	2.6	−18	12.5	+0
C III]	1908.71	45.8	−31	20.6[f]	−7	36.0[g]	+9

[a] 10^{-13} ergs cm^{-2} s^{-1}.
[b] Corrected for $v_{\rm radial} = -25$ km s^{-1} (Hollis et al. 1986, 1990).
[c] Emission double peaked; blue peak @ −79 km s^{-1}, 0.4 × 10^{-13} ergs cm^{-2} s^{-1}.
[d] Emission double peaked; blue peak @ −97 km s^{-1}, 3.0 × 10^{-13} ergs cm^{-2} s^{-1}.
[e] Single peaked profile.
[f] 3x overexposed.
[g] 2x overexposed.

An absorption feature is also present ∼ −83 km s^{-1} in the C IV λλ1548, 1550 lines (Fig. 3, *bottom panel*) from a HIRES SWP spectrum obtained of the northeast jet (SWP 29543; 675 minute exposure) (1986 October 27; epoch 1986.82). The spectrum of the jet was obtained by placing the 10″ × 20″ entrance aperture on the brightest northeast emission knot ∼7″, ensuring the central H II region and star were sufficiently far outside the aperture to avoid scattered light contributions (Michalitsianos et al. 1988a).[2]

The velocities associated with the absorption feature present in the central H II region and jet (Fig. 3, *middle and bottom panels*) are consistent with the polar expansion velocities found in the northeast inner nebula that range up to ∼200 km s^{-1}; the northeast jet is directed toward the observer ∼5°, and out of the plane of the sky. We propose this absorption arises from foreground material associated with the expanding northeast inner nebula, consistent with the geometry of the northeast jet knots proposed by Solf (1993). The blue asymmetric C IV emission wing observed on 1987.42 (Fig. 3, *middle panel*), therefore, corresponds to the high-velocity collimated wind that is streaming inside the northeast inner nebula, against which the northeast inner nebula absorption is observed. Accordingly, absorption is also observed at jet position (Fig. 3, *bottom panel*), where features B+D are seen through foreground material associated with the expanding northeast inner nebula.

In our most recent HIRES spectrum of the central H II region a displacement of the C IV velocity centroid is evident on 1992.99 (Fig. 3, *top panel*) and corresponds to a redshift of ∼ +23 km s^{-1}. Moreover, the emission wing is predominantly redward of the systemic velocity and extends to ∼ +180 km s^{-1}; an additional emission feature is present at ∼ +203 km s^{-1} (arrow in Fig. 3, *top panel*). The reversal of line profile asymmetry between 1987.42 and 1992.99 significantly reduced the contrast between absorbing material associated with the northeast inner nebula and collimated wind. This is consistent with models that propose the R Aqr jet is largely one-sided. Absorption from material in the southwest inner nebula may be reflected in the slope of the red emission wing (Fig. 3, *top panel*). In this case, the emission feature at +203 km s^{-1} results from the southwest inner nebula absorption that is superposed on the extended red wing emission of C IV, and produces an emission minimum ≤ +180–190 km s^{-1}.

[2] Note the C IV I(λ1548)/I(λ1550) in the central H II region is less than the optically thick limit of unity, while the doublet ratio suggests optically thin conditions in the northeast jet. The nature of anomalous C IV doublet intensities is understood in terms of strong optical depth effects in the line core that includes the effects of self-absorption and Bowen-pumping of Fe II multiplet (45.01) by the C IV λ1548.2 doublet member (Michalitsianos et al. 1992).

4. SUMMARY AND CONCLUSION

The evolution of the C IV line profile structure in R Aqr following the appearance of a brilliant jet in 1980 provides important clues concerning the nature of mass expulsion in symbiotic stars. The reversal of C IV line profile asymmetry of a

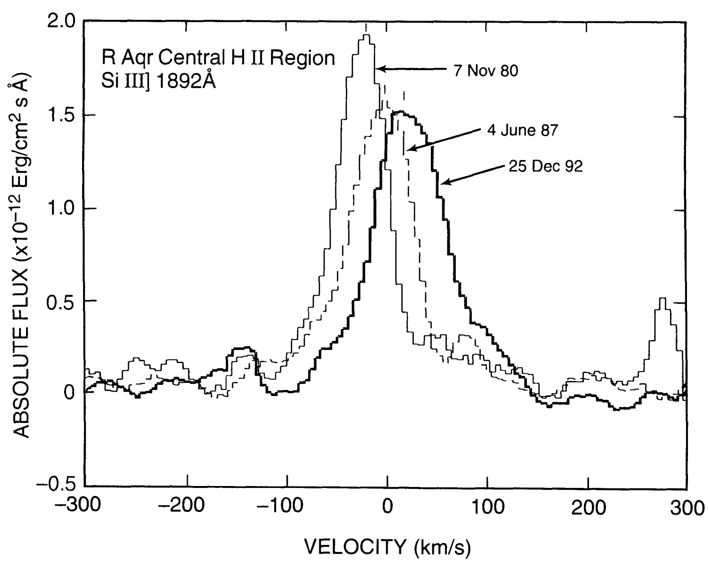

Fig. 2.—Line profile emission from Si III] λ1892 obtained when the *IUE* 10″ × 20″ entrance aperture was positioned on the R Aqr and central H II region (feature C1): *solid line*: 1980.85 (SWP 10558) 240 minute exposure; *dashed line*: 1987.42 (SWP 31102) 770 minute exposure; *thick line*: 1992.99 (SWP 46585) 395 minute exposure. The velocities are corrected for the systemic motion of −25 km s^{-1}. The continuum adjacent to the line is not adequately exposed and the absolute fluxes indicated are above background.

blueward-to-redward extended wing supports the view that the high-velocity collimated wind (or stream) (Paresce et al. 1991; Kafatos et al. 1986) is essentially one-sided, altering direction on a timescale ~1 decade.

Assuming that the counterflow wind started in early 1992, the appearance of emission knots is expected when the counterflow interacts with slower moving material in the southwest inner nebula. For example, feature A' (PA = 225°; Fig. 1) has a velocity relative to the systemic motion ~ +8 km s^{-1} and is ~1".5 from the central H II region and star (C1) (Hollis et al. 1990). At a distance $d = 250$ pc, and assuming a constant flow speed in the range 200–500 km s^{-1}, the counterwind will collide with feature A' sometimes between ~9 and ~3.5 years, respectively, from now. If correct, our interpretation predicts the northeast jet parcels will diminish in intensity as the southwest parcels increase in brightness.

Continued monitoring with high-resolution, ground-based optical and spaceborne UV imaging in nebular lines and radio interferometry is critically needed to determine if collimated mass flow leads to the formation of a bright counter jet in a few years. The timescale for the appearance of such structure would suggest that the direction of mass flow is dependent on the binary orbit phase. Estimates of the orbit period are uncertain and range between a 27 yr period determined from radial velocity measurements of Merrill (1950), and a ~44 yr eclipsing period obtained from visual photometry. If a precessing thick-accretion disk is present (Kafatos et al. 1986; Michalitsianos et al. 1988b), flow from one disk pole could be obstructed by the extended envelope and atmosphere of the Mira variable, depending on the orientation of the disk and the changing projection angle associated with a precessing jet. This could explain the apparent one-sidedness of the R Aqr jet. Alternatively, the shift in the ejection from one pole to the other could result if the axis of the disk along which ejection occurs is fixed in space. As the two stars orbit around each other, the direction of ejection would be shift from one pole to the other after half a period.

We wish to thank the IPC staff of the *IUE Observatory* for reprocessing these data and assistance with applying the appropriate heliocentric velocity corrections to the data. We also thank the anonymous referee for useful suggestions for improving the text.

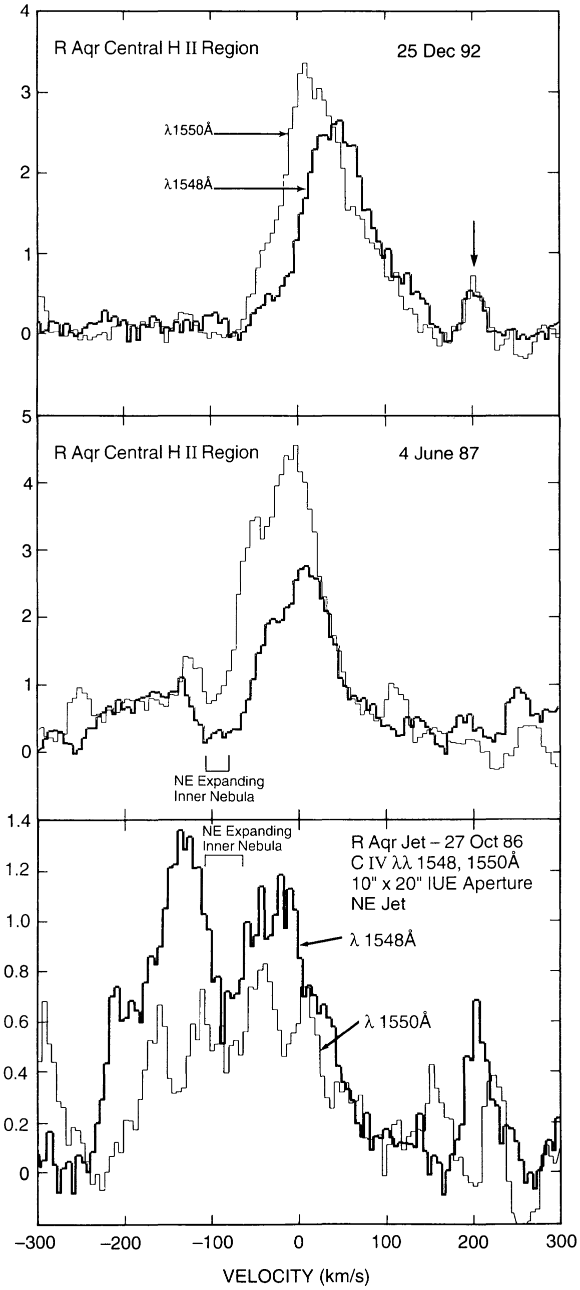

FIG. 3.—The C IV λλ1548, 1550 are plotted on a common velocity scale after correcting for systemic motion of −25 km s^{-1}; *thick line*: λ1548 line; *thin line*: λ1550 line. The intensity of the C IV λ1548 doublet member is weaker compared with the λ1550 doublet member in the central H II region, which is attributed to strong self-absorption in the line core, and Bowen-pumping of Fe II multiplet (45.01) by the C IV λ1548 Å line (Michalitsianos et al. 1992). (*Top*) 1992.99 (SWP 46585) 395 minute exposure obtained of R Aqr–central H II region (feature C1). The broad wing extends to velocities of ≥ +200 km s^{-1}, indicating a strong red asymmetry. An emission feature at +203 km s^{-1} (indicated by the arrow) is also present. (*Middle*) 1987.42 (SWP 31102) 770 minute exposure obtained of the R Aqr–central H II region (feature C1). Absorption corresponding to the northeast inner nebula is indicated by a bracket. The doublet exhibits a blue extended wing suggesting outflow velocities along the northeast inner nebula that peak at ≳ −200 km s^{-1}. An additional velocity component is also present at ~ −50 km s^{-1} which are resolved in the line core. (*Bottom*) 1986 October 27 (epoch 1986.82) (SWP 29543) 675 minute exposure of the northeast jet knots (features B+D) obtained by offsetting the *IUE* 10" × 20" entrance aperture ~7" northeast from the central star. The aperture was centered at the position corresponding to the brightest radio knot in the northwest jet (Michalitsianos et al. 1988a). Absorption with a velocity centroid at −83 km s^{-1} corresponding to the northeast inner nebula is indicated by a bracket. The full base width ~300 km s^{-1} of the doublet profiles is consistent with the flow speeds estimated for the collimated wind.

REFERENCES

Herbig, G. 1980, IAU Circ., No. 3535
Hollis, J. M., Kafatos, M., Michalitsianos, A. G., & McAlister, H. A. 1985, ApJ, 289, 765
Hollis, J. M., Michalitsianos, A. G., Kafatos, M., Wright, M. C. H., & Welch, W. J. 1986, ApJ, 309, L53
Hollis, J. M., Wright, M. C. H., Welch, W. J., Jewell, P. R., Crull, H. E., Jr., Kafatos, M., & Michalitsianos, A. G. 1990, ApJ, 361, 663
Merrill, P. W. 1950, ApJ, 112, 514
Kafatos, M., Michalitsianos, A. G., & Hollis, J. M. 1986, ApJS., 62, 853
Michalitsianos, A. G., & Kafatos, M. 1988, in IAU Colloq. The Symbiotic Phenomena, 103, ed. J. Mikolajewska, M. Friedjung, S. J. Kenyon, & R. Viotti (Dordrecht: Kluwer), 245
Michalitsianos, A. G., Kafatos, M., Fahey, R. P., Viotti, R., Cassatella, A., & Altamore, A. 1988a, ApJ, 331, 477

Michalitsianos, A. G., Kafatos, M., & Meier, S. R. 1992, ApJ, 389, 656
Michalitsianos, A. G., Oliversen, R. J., Hollis, J. M., Kafatos, M., Crull, H. E., & Miller, R. J. 1988b, AJ, 95, 1478
Paresce, F., et al. 1991, ApJ, 369, L67
Solf, J. 1993, A&A, 257, 228
Solf, J., & Ulrich, H. 1985, A&A, 148, 274
Sopka, R. J., Herbig, G., Kafatos, M., & Michalitsianos, A. G. 1982, ApJ, 258, L35
Spergel, R. J., Guiliani, J. L., Jr., & Knapp, G. R. 1983, ApJ, 275, 330
Willson, L. A., Garnavich, P., & Mattei, J. L. 1980, Inf. Bull. Var. Stars, 1961–1963