# HR 2142, Thirty Years After it was Hypothesized to be an Interacting Binary

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**The current status of our knowledge of the HR 2142 system is reviewed. The mass flow in the system and its long-term behavior are currently being studied using *IUE* HIRES data obtained between 1979–95 and archival *Copernicus* observations acquired in the late 1970s. Some recent results are summarized here. The strength and velocity behavior of the infall components to the Si II, IV lines seen during the *primary* shell phase from $\phi$ ~0.70–0.98 resemble that observed in conventional Algol systems. The inferred mass infall rate of $\sim 10^{-7}$ $M_\odot$ $yr^{-1}$, however, is too small to account for the massive H$\alpha$-emitting disk about the primary. The cause for the mass outflow observed during the *secondary* shell phase is still unknown. The nature of the secondary star, which remains undetected, is discussed. The small amount of residual flux in the UV that might be attributed to the secondary weakens the assumption that it must be an O subdwarf as in the $\phi$ Per system, but further studies are warranted.**

**Keywords:** Be stars – close binary stars – stars: individual: HR 2142

## 1 The HR 2142 Binary System: Historical Background

It was during the course of my first conversation with Mirek Plavec in October of 1970 that Mirek put forth the suggestion that HR 2142 might be an interacting binary. In the optical spectral region HR 2142 (HD 41335, V696 Mon, B1.5 IVnne, $v \sin i = 350$ km s$^{-1}$) has all the appearances of a "classical" Be star, but it is unusual in that transient Balmer shell lines are observed periodically every 80.86 days (Peters 1971, 1972). Ground-based spectra obtained in the early 1970s revealed that the 'shell' phase has two components, each of which displays a characteristic strength and velocity behavior. The first segment, which lasts about 5–8 days in the optical region, is characterized by shell features that are red-shifted relative to the photospheric lines. They peak in strength $\sim 5^{\rm d}$ after they are first detected then disappear $\sim 3^{\rm d}$ afterwards. The velocities steadily decrease from ~100 to 20 km s$^{-1}$ throughout this stage. About 2–3$^{\rm d}$ after their disappearance, the shell lines reappear at their previous maximum strength for about 3$^{\rm d}$, but display negative radial velocities. Following the terminology adopted in the 1970s, the first segment of the two-component shell phase is called the *primary* shell phase while the second part is referred to as the *secondary* shell phase. Our first empirical binary star model for HR 2142 based solely upon the behavior of the shell lines was presented at IAU Symposium 51 (Peters 1973).

HR 2142 was eventually confirmed to be a binary and its ephemeris and spectroscopic behavior appeared to support the suggestion that it is an interacting binary Be star with a massive accretion disk and a large rate of mass transfer (Peters 1983). The periodic shell activity seen earlier was explained by the fact that our line-of-sight to the mass gainer in the system sweeps through the gas stream and 'counterstreaming' material once every orbital period. HR 2142 is a single-line spectroscopic binary, and if the mass of the primary is representative for its spectral type (about 10–11 $M_\odot$, Harmanec 1988), and the inclination of the system is $\sim 75°$, the semimajor axis for the system is 0.81–0.84 A.U. The strong Balmer emission (the peak intensity of H$\alpha$ is 4.0 $I_{\rm cont}$) suggests the presence of a massive circumstellar (CS) disk that probably extends out to the limit of the Roche surface of the primary (Peters 1976). Because of the very conspicuous on-going mass flow toward the primary, several have assumed that the secondary star fills its critical Roche surface, but the spectrum of the secondary has never been observed. The absence of spectral signatures of a cool companion in the IR region led Waters et al. (1991) to suggest that the secondary is a helium subdwarf. From 1979 to 1995 HR 2142 was semi-regularly observed with the HIRES cameras on the *IUE* spacecraft. About 100 SWP and 50 LWP/LWR HIRES images were acquired. These images provide a unique and valuable database for investigating the mass flow in the system and its long-term behavior. Combined with archival data from the *Copernicus* satellite, the *IUE* observations also allow us to put limits on the UV brightness of the still undetected secondary. Some recent results from an on-going UV study of the mass flow and search for the elusive secondary are summarized in this paper.

## 2 The Spectroscopic Behavior in the UV Region

The *IUE* images used for this study are MXHI files that were processed with the NEWSIPS software (Nichols & Linsky 1996). All were downloaded from the MAST archive at the Space Telescope Science Institute. The data contain information on mass loss from a stellar wind and mass infall/outflow associated with the apparent ongoing mass transfer.

At first glance the C IV wind absorption in HR 2142 appears typical for a B1.5e star, but the *IUE* database reveals significant phase-dependence. From the grayscale display in Fig. 1, one can readily see an "S-shaped" pattern in the wind absorption versus phase. A conspicuous infall component (additional redshifted absorption) is observed on the *trailing* hemisphere of the system. Near phase 0.5 one observes an increase in the equivalent width of the C IV wind lines. This effect is commonly observed in Algol-type binary systems (Peters 2001). There is some evidence for variability in this wind enhancement on a time scale of many orbital cycles (~9), but the data are too sparse to claim this with any certainty. The wind strength also appears to be enhanced during the *secondary* shell phase (an infall component is not observed here). Similar wind behavior is observed in the Si IV resonance doublet.

Mass infall/outflow is observed in many UV features observed with *IUE*, but perhaps the most useful are the resonance doublets of Si II. These are UV 1 ($\lambda\lambda$ 1808, 1817), UV 2 ($\lambda\lambda$ 1526, 1533), UV 3 ($\lambda\lambda$ 1304, 1309), UV 4 ($\lambda\lambda$ 1260, 1264), and UV 5 ($\lambda\lambda$ 1190, 1197). Two attributes that make these lines so useful are that they have $f$-values that show an enormous range, from 1.2 ($\lambda\lambda$ 1260, 1264) to 0.006 ($\lambda\lambda$ 1808, 1817) and, in each pair one member of the doublet lies sufficiently above ground, 287 cm$^{-1}$, that an interstellar component does not contaminate it. Column densities from unsaturated lines are by far the most reliable. From the Si II doublets alone one can reliably determine line-of-sight column densities that differ by more than a factor of 200. In HR 2142 unsaturated lines from one or more of the Si II doublets are seen at all phases in which we view the primary through CS material. In one extreme, we observe Si II $\lambda$ 1817 as we view the primary through the densest portion of the infalling material ($\phi$ = 0.96), whereas in the other we barely detect an enhancement

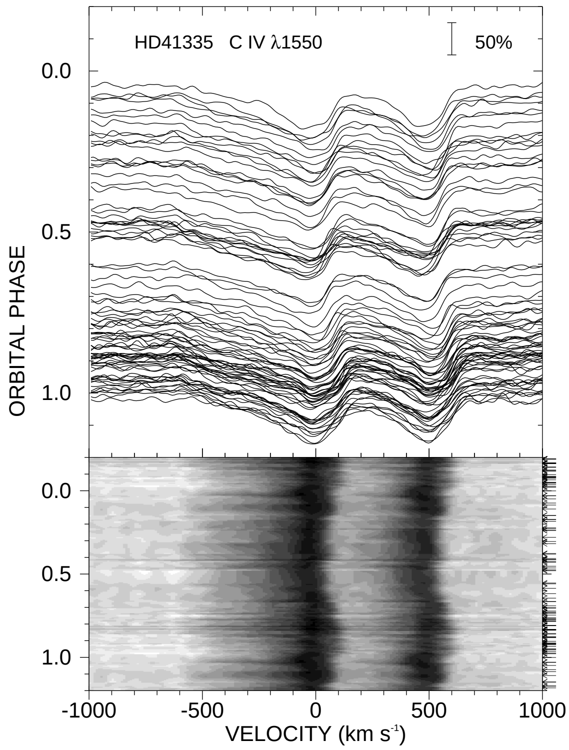


**Fig. 1**: The phase-dependent wind absorption in HR 2142. The *upper panel* shows the individual profiles of the C IV resonance double plotted vertically versus orbital phase. In the *lower panel* these profiles are displayed as a grayscale plot with the darkness increasing with line absorption. The arrows to the right of the display indicate the locations of the individual images shown above. Note the wavy appearance of the wind absorption, especially the infall component between 0.7 $\leq \phi \leq$ 0.9.

in $\lambda$1264 as our line-of-sight just intercepts infalling plasma. Another set of lines that are useful for investigating the dense portions of infalling/outflowing material are the Ti III resonance lines near $\lambda$1290 Å (UV 1 & 2) because the low abundance for Ti renders the lines intrinsically weak.

The nature of the infalling/outflowing regions is demonstrated well by the behavior of the $\lambda$1264 line (Fig. 2). Absorption from the CS material can be seen as early as phase 0.7. Upon its first detection, the velocity is comparable with that of the photosphere but increases steadily to about 130 km s$^{-1}$ at phase 0.97. This is different from the velocity behavior seen in the Balmer lines (Peters 1983) that display a more positive velocity around phase 0.90. The strength rapidly falls and the velocity approaches the photospheric value as the system reaches conjunction. The line strength then rapidly increases and the feature becomes violet-shifted as the *secondary* shell phase commences. The quantitative behavior of the Si II 1264 Å feature is shown in Fig. 3 in which the equivalent width and velocity of the CS line is plotted ver-

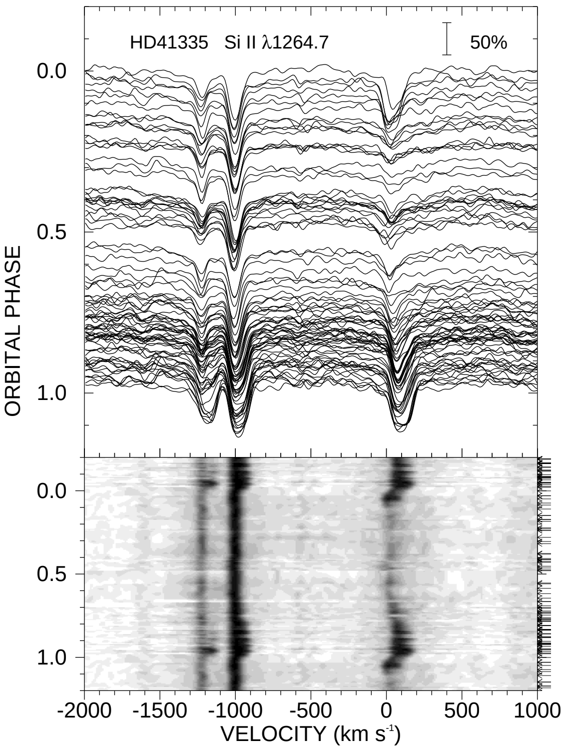


**Fig. 2**: The same type of display as in Fig. 1 for the Si II $\lambda\lambda$1260,1264 doublet. The velocities are plotted relative to the $\lambda$1264 component and are not corrected for the radial velocity of the primary. The prominent features seen are S II $\lambda$1259 and the Si II doublet. The S II and Si II 1260 lines contain interstellar components. The broad, faint absorption in $\lambda$1264 seen between the "shell" phases is the photospheric line plus a weak disk component. Note the strength/velocity behavior of the absorption feature formed in the CS material.

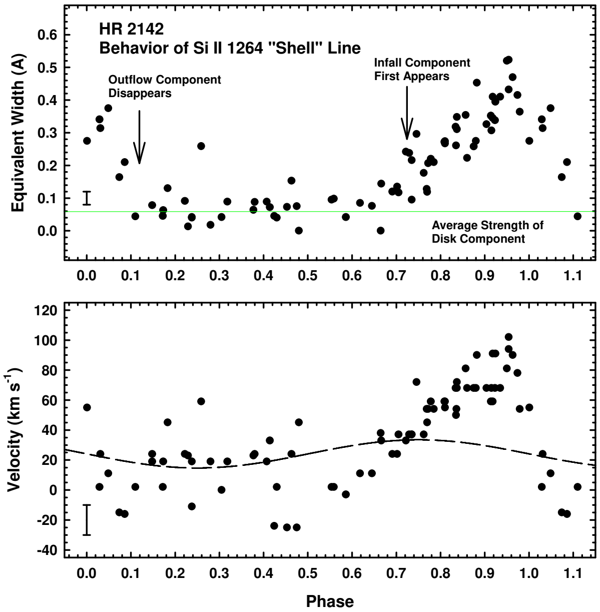


**Fig. 3**: The equivalent width and centroid velocity of the non-photospheric absorption component in the Si II 1264 Å line versus phase. The arrows indicate the locations of the disappearance/appearance of the outflow/infall features. The average EW of the underlying, non-varying feature that is probably formed in the disk is shown with a horizontal line. The *dashed* line in the lower panel shows the radial velocity curve for the primary from Peters (1983).

sus phase. The infall component is definitely seen as early as phase 0.70. Note that the outflow component observed during the *secondary* shell phase is seen between phases 0.02–0.09 with a maximum strength at phase 0.05. The Balmer shell lines are not detectable after phase 0.05. There is a striking asymmetry between the *primary* and *secondary* shell phases, just as has been observed in the optical region. The *primary* shell phase is seen over a phase of $0^{\mathrm{P}}.30$, but the duration of the *secondary* shell phase is only $0^{\mathrm{P}}.10$. From the velocity plot it is apparent that, relative to the photosphere, the velocity of the infalling material is twice that of the outflowing plasma.

Non-photospheric Si II 1264 Å absorption is seen at all phases. The underlying component apparent in Fig. 3 is probably formed in the disk about the primary. The feature is seen in this line simply because the log $gf$ is very large. The line appears to display a negative velocity between phase 0.40–0.50, which indicates it is formed in the general flow associated with the enhanced C IV wind at this phase.

Evidence for long-term variability in the infalling material is seen (Fig. 3). A long-term trend, $\sim$3–5 cycles, in the "strengths" of the shell phases has been long known (Peters 1972). Whether this is associated with the apparent $344^{\mathrm{d}}$ (4.25 cycle) photometric period found by Mennickent, Sterken, & Vogt (1998) remains to be determined.

# 3 The Secondary Star

More than twenty years after the Lick Observatory spectrograms confirmed that HR 2142 is a spectroscopic binary (Peters 1983), the spectrum of the secondary star still has not been observed. At this point it might be worthwhile to summarize what we do know about the system. The period (80.860 $\pm$ 0.005 d) and mass function (0.007 $\pm$ 0.002 $M_\odot$) are well-known (Peters 1983). As Harmanec et al. (1983) failed to observe an eclipse, the inclination of the system must be $< 77°$ if the secondary fills its critical Roche surface. If the inclination is $\sim 75°$ and the mass of the primary is $\sim$10 $M_\odot$ (Harmanec 1988), the implied secondary mass is $\sim$1 $M_\odot$. Even though more than 135 orbital cycles have elapsed, recent ground-based H$\alpha$ observations with the Coudé Feed Telescope at Kitt Peak National Observatory indicate

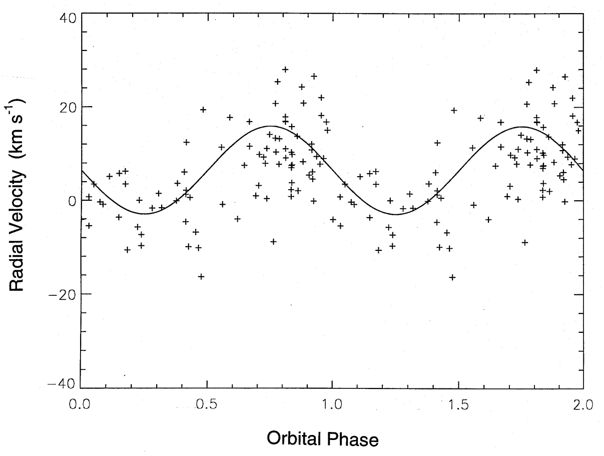


**Fig. 4**: The radial velocities from a cross-correlation analysis of the *IUE* SWP HIRES images. The curve plotted with the *solid* line is from Peters (1983) normalized to the mean velocity from the *IUE* data.

that the ephemeris in Peters (1983) is still valid. Velocities obtained from a cross-correlation study *IUE* SWP data also lend support to the 1983 results (Fig. 4).

Traces of a cool secondary have yet to be detected in the IR. Waters et al. (1991) used published UV, optical, and IR photometry on HR 2142 to search for a signature of a cool secondary. The failure to find evidence for such a star led the authors to hypothesize that the secondary is a helium subdwarf similar to that which has been confirmed in $\phi$ Per, a binary Be star that superficially looks like HR 2142 in the optical spectral region. In the study of Waters at al. (1991) the flux distribution in HR 2142 was compared with that in KX And, an interacting binary Be star with a cool companion whose spectrum has been observed (Floquet et al. 1995). The H$\alpha$ emission strength relative to the continuum is comparable in both systems, but as KX And appears to be a cooler and much less luminous star,[1] its H$\alpha$-emitting disk is probably significantly smaller. From data in Floquet et al. (1995), the implied dimension of the KX And system is ~60% that for HR 2142, but the inferred size of the cool secondary is about the same (~32 $R_\odot$). Considering the above factors and the fact that the UV/optical flux in KX And is affected by extensive line and continuous absorption from its disk, one would expect the signature of the secondary illustrated in Fig. 2 of Waters et al. to be much more prominent. Waters et al. (1991) in fact admit that if the secondary and disk contribute <30% and >15%, respectively, in the near IR then the secondary might go undetected. It is likely that the disk does contribute more flux in the IR, but if the secondary fills its Roche surface, has a temperature of about 6000 K, and is not underluminous the ratio of its flux to that contributed by the primary at 1.65$\mu$ should be about 5.5 times.[2] As the analysis of Waters et al. (1991) was quite model-dependent, it would be worthwhile to recompute the expected IR continuum considering all three components (hot primary, cool secondary, massive Be disk) using a higher, more representative temperature (25,000 K, instead of 20,000 K) for the primary and a cooler temperature for the CS disk (cf. Millar & Marlborough 1999, who present evidence that the disk temperatures of Waters et al. 1987 are too high).

Following the detection of an sdO secondary in the $\phi$ Per system from *HST* (Gies et al. 1998) and *IUE* data (Thaller et al. 1995) with the aid of a Doppler tomography code (Bagnuolo et al. 1994), it appeared reasonable to use this same code to search for a similar star in HR 2142 as its optical spectrum bears some similarity to $\phi$ Per and both have long periods. This investigation continues, but as of the date of this meeting, the search has been unsuccessful. Upper limits on the UV flux from such a subdwarf can be obtained by measuring the residual flux in the cores of the very saturated features that are observed at the peak of the *primary* or *secondary* shell phase ($\phi \sim$ 0.95-97, 0.03). Fortunately many *IUE* images in this phase interval are available as well as some archival data taken in the late 1970s with the *Copernicus* satellite. The spectrum observed at phase 0.95 in the regions $\lambda\lambda$1170–1200 Å and $\lambda\lambda$1860–1900 Å are shown in Fig. 5. These intervals contain many saturated lines of C III, Si II, or Fe III. The deepest residual intensity observed is 7–8% of the continuum. In Fig. 6, I show observations of one of the resonance lines of Fe III (UV 1) obtained with the *Copernicus* U1 spectrometer during *primary* and *secondary* shell phases in the late 1970s. These features become very saturated during the shell phases but are barely detected throughout most of the orbit. The residual intensity observed is 11–13% of the continuum. There is some evidence that the apparent "extra" UV flux becomes greater as the wavelength decreases, but the result is not statistically significant and one cannot be entirely sure the background subtraction for the data is better than a few percent.

[1] The most frequently quoted spectral type for KX And is B3IVe-shell (Štefl et al. 1990 showed from photometry that it apparently varies from B1 to B6), but often times it is simply called Bpe. As it is a peculiar shell star, it is almost impossible to reliably determine its reddening and absolute flux at H$\alpha$. KX And is $2^{\mathrm{m}}\!.2$ fainter than HR 2142, but their distances from the *Hipparcos* Catalog are 282 & 446 pc, respectively. Its absolute magnitude, therefore, must be ~1 mag fainter than that for HR 2142.

[2] Using a radius of 6 $R_\odot$ for the primary (Harmanec 1988, allowing for an equatorial increase due to the star's rapid rotation of about 0.6 $V_{\rm crit}$), 31.5 $R_\odot$ for the secondary, and fluxes for model atmospheres of ($T_{\rm eff}$/log $g$) 25000/4.0 & 6000/1.5 from Kurucz (1994).

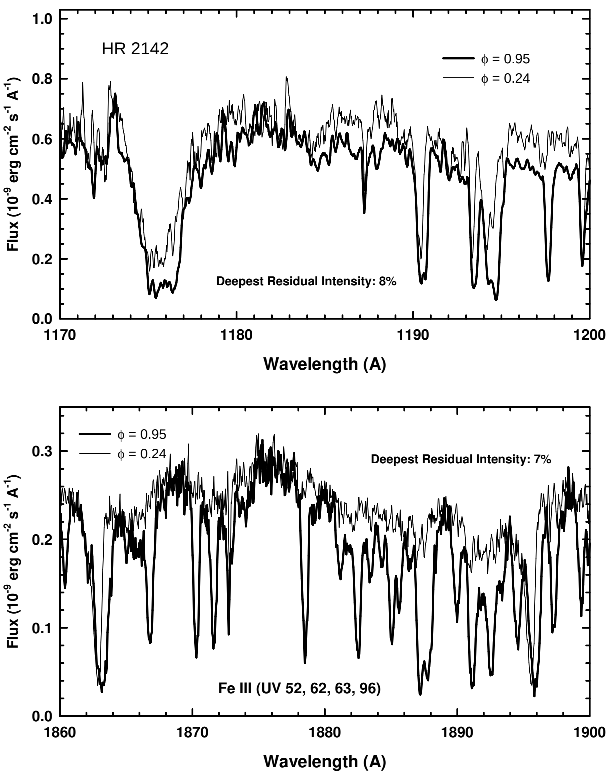


**Fig. 5**: An *IUE* spectrum taken at phase 0.95 during the *primary* shell phase is compared with one obtained at quadrature. Both spectral regions displayed contain many infall lines that are saturated at the peak of this shell phase. At best 7–8% of the light can come from the secondary star.

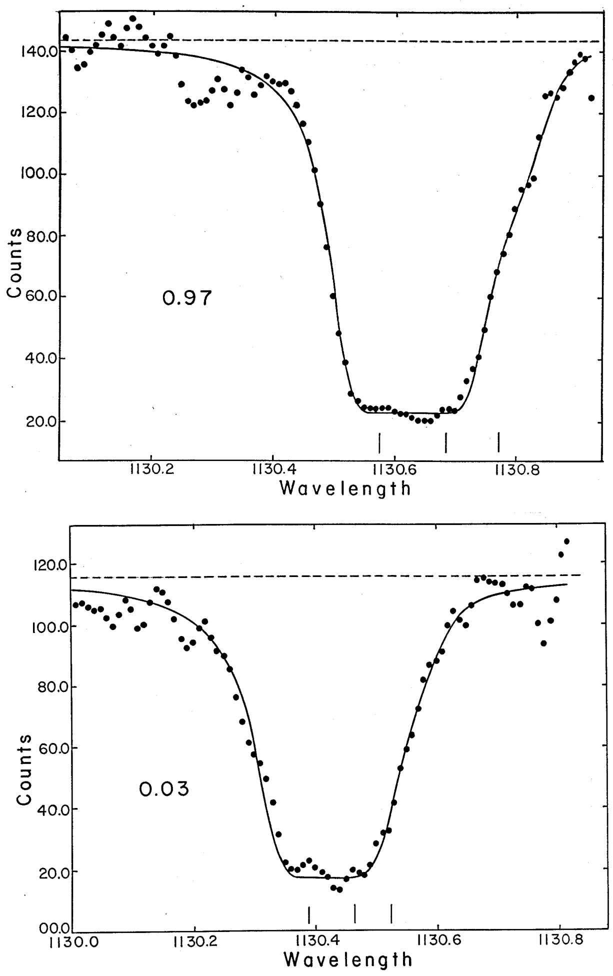


**Fig. 6**: Fe III 1130.404 Å observed with the *Copernicus* satellite on 26 October 1977 ($\phi$=0.97) and 20 January 1978 ($\phi$=0.03) during the *primary* and *secondary* shell phases, respectively. The residual flux was 11–13% of the continuum.

# 4 Current Thoughts on the HR 2142 System

In my opinion the most important objective for future research on HR 2142 should be to observe the spectrum of its secondary. Until the nature of this star is known, it will be impossible to fully interpret the mass infall and outflow that is conspicuously seen. In this paper I have chosen to refer to the mass flow toward the primary as an "infall" of material rather than a gas stream. The strength and velocity behavior of the infall lines, and the wide interval over which they are observed ($0.70 < \phi < 0.98$) is virtually identical to what is seen in many B-type Algol systems of shorter period than HR 2142 (Peters 2001). By comparison, therefore, it appears reasonable to associate the infall region with a gas stream. However, the typical mass infall rate of $\sim 10^{-7}$ M$_\odot$ yr$^{-1}$ found from the analysis of the weak Si II and Ti III shell lines is too low to be responsible for the massive H$\alpha$-emitting disk about the primary. The disk is most likely a result of surface activity on the Be star that produces the Be phenomenon and not current mass transfer. The net mass gained from accretion is probably a second-order effect.

The outflow seen in the *secondary* shell phase is more difficult to interpret. Many Algols show evidence of an interaction between the returning material from the gas stream and the main gas stream. Sometimes it is just an enhancement in H$\alpha$ emission (Richards 1992), while other times high ionization species such as N V are observed (Peters 2001). Observation of HR 2142 over a span of 30 years confirms that the region responsible for the *secondary* shell phase is quite stable and narrow in phase. Perhaps we are observing part of a "polar jet", such as those that have been detected in the Algols $\beta$ Lyr (from optical interferometry, spectroscopy, and photometry, Harmanec et al. 1996, and UV and optical polarimetry, Hoffman, Nordsieck, & Fox 1998), V356 Sgr and TT Hya from *HST*/FOS spectropolarimetry (Lynch et al. 1996, Polidan, talk presented at this meeting).

The UV data do not rule out the possibility that the secondary in HR 2142 is an O subdwarf. However, at best it contributes half the flux (relative to the primary) that one observes in $\phi$ Per (Gies et al. 1998). As HR 2142 is intrinsically fainter than $\phi$ Per, this implies a much smaller star than the 1.3$R_\odot$ object in the $\phi$ Per system. The secondary might be a B subdwarf, but this would be very difficult to explain from the standpoint of stellar evolution. As X-ray emission has never been observed from HR 2142, it is very unlikely that the secondary is a white dwarf or neutron star.

As mentioned above, it might be interesting to look at the IR energy distribution again and produce a model that contains a brighter disk and hotter primary. But it is entirely possible that the secondary is not in thermal equilibrium (underluminous) or that it does not fill its Roche surface. There is evidence that the secondaries in some Algol systems in their late stages of evolution (e.g. DN Ori, S Cnc) are detached from their Roche lobes (Etzel & Olson 1995). The case of DN Ori is especially interesting as the late B primary in this $13\overset{\mathrm{d}}{.}0$ binary has an H$\alpha$-emitting disk and is rotating supersynchronously. The presence of the disk implies that some mass transfer is still occurring, but the disk could be from Be-type activity.

At the conclusion of this paper, I present an illustration of the HR 2142 system as we perceive it in the year 2000. The "model" in Fig. 7 has been drawn to include a secondary that is either a cool star that fills its Roche surface or an O-type subdwarf. The true nature of the secondary might turn out to be something entirely different from the alternatives considered here. Eventually the elusive secondary in this interesting, active system will be detected and its parameters measured. Afterwards the cause for the mass infall and outflow should become apparent.

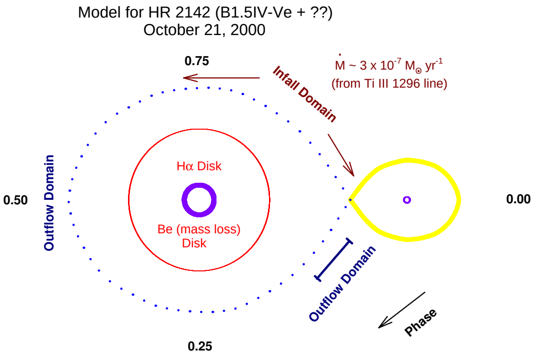


**Fig. 7**: Our perception of the HR 2142 system as of 2000 October. Domains of infall and outflow are indicated. The small circle on the left is the primary, while our current uncertainty in the nature of the secondary is indicated by the *either/or* star on the right. Possible secondaries include a Roche-lobe filling cool star or an O-type subdwarf. The *dotted* figure shows the Roche surface for the primary.

## Acknowledgement

Much of the current work on HR 2142 reported here, especially the interpretation of the *IUE* database, continues and is being carried through in collaboration with Douglas Gies. I thank Doug for supplying Figures 1, 2, & 4 and for many fruitful discussions. I am grateful for partial support for this project from NASA Grant NAG5-9124.

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