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HUBBLE SPACE TELESCOPE OBSERVATIONS OF THE ECLIPSING BINARY VV CEPHEI

or

HOW AN ASTRONOMER CAN WORK ON ONE OBJECT FOR OVER 20 YEARS AND STILL REMAIN INTERESTED

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VV Cephei is an eclipsing binary system consisting of an M supergiant primary star and a hot component of unknown type which is most likely a main-sequence B star. The orbital period is 20.3 years. The orbital parameters have been determined by using absorption lines from the M star and H-alpha emission which was assumed to be centered around the hot component. Both stars are 20 solar masses. The diameter of the M supergiant has been determined from eclipse observations and values range from 1600 to 1900 solar radii. If the M star radius were 1800 solar radii, it would just fill its Roche Lobe at periastron. The orbital eccentricity is 0.35; at apastron the stars are separated by about four primary star radii, and the M supergiant is well within its Roche Lobe.

The primary star is sufficiently cool and luminous to be losing a significant amount of matter in a stellar wind, similar to Alpha Orionis and other M supergiants. These stars are losing about 10^{-6} solar masses per year which forms an extended circumstellar envelope. Despite decades of research effort, the mechanism of this mass loss is as yet unknown. The acceleration apparently occurs within the region extending out to a few stellar radii, so probing this region of an M supergiant's atmosphere should provide insight into the origin of these winds.

The Zeta Aurigae binaries are eclipsing systems with K supergiant primaries and B main-sequence companions. As the B star goes into eclipse behind the K star primary, its orbital motion allows it to become a probe of the extended K star atmosphere. As the B star's light shines through more and more of the K star atmosphere, more absorption from the K atmosphere is seen in the combined spectrum. During egress from eclipse, the absorption from the K supergiant atmosphere gradually weakens. In the ultraviolet region of the spectrum, the K supergiant is much fainter than the hot component, and the out-of-eclipse ultraviolet spectrum is that of a normal main-sequence B star.

I became interested in atmospheric eclipses while doing my Ph.D. thesis work on mass loss from M supergiant stars. In this work, I used infrared photometry to measure silicate dust emission from their winds, and optical spectroscopy to study circumstellar gas. This gas is detected through sharp absorption cores superimposed on strong photospheric absorption lines arising from transitions with lower levels below excitation potential of about 1 eV. These narrow features are blue-shifted by about 10 km/sec due to the expansion of the circumstellar envelope.

When I finished my Ph.D., I went to the Harvard-Smithsonian Center for Astrophysics for a postdoctoral fellowship to continue studying the gas-to-dust ratio in M supergiant circumstellar envelopes. When I arrived, I learned that Dr. Andrea Dupree and her collaborators had just been granted time on the soon-to-be-launched International Ultraviolet Explorer (IUE) satellite to study VV Cephei as the hot component emerged from eclipse behind the M supergiant in 1978. I was thrilled to join this collaboration to study the structure of the M supergiant as the hot component moved out from behind it.

Unfortunately, IUE was not launched in time to observed VV Cephei during total eclipse. The first observation was made during the partial phase of egress from eclipse, and observations continued throughout egress. However, unlike the Zeta Aurigae stars, the hot component never appeared to emerge fully from eclipse. Although some absorption features weakened and eventually disappeared, the hot component remained shrouded in a rich absorption spectrum.

At the time of our first publication on the IUE data, in 1980, the majority of these absorption features remained unidentified. Astronomical spectroscopy in the ultraviolet was a brand-new field, and physicists had not yet compiled lists of expected transitions. However, by the mid-1980's, ultraviolet line lists had begun to appear. I used a compilation by R. L. Kurucz and was able to identify nearly all of the absorption features seen in the deep atmospheric eclipse phase of the Zeta Aurigae system 31 Cygni. These lines arose from neutral and singly ionized elements, overwhelmingly from the iron group, with lower levels up to about 4 eV. Nearly all these lines were seen in the spectrum of VV Cep, even out of eclipse, with the exception of neutral lines which had disappeared during egress. The upper panel in Fig. 1 compares an out-of-eclipse spectrum of VV Cep (taken near third quadrature) with the eclipse spectrum of 31 Cyg. Note that most of the absorption features match up, but that there are absorption features in VV Cep which do not appear in 31 Cygni. A further difference is seen in the presence of emission lines in the spectrum of VV Cep that are not seen in 31 Cyg. (The vertical lines in Fig. 1 mark multiplet UV 9 of N I.)

As I continued to study these UV spectra, I found a better spectral analog to VV Cephei in 28 Tauri (Pleione of the Pleiades). 28 Tau is a variable Be star which was undergoing a strong shell phase in the early 1980's. As one of my original collaborators, John Black, stated, we should not have been surprised that the hot component outside of eclipse should look like a Be-shell star. The lower panel of Fig. 1 compares the same region of VV Cephei's spectrum to that of 28 Tau during its strong shell phase. Note that the absorption features which are seen in VV Cep but not in 31 Cygni do in fact appear in the spectrum of 28 Tau. I have not yet attempted a comprehensive identification of these lines, but those that have been identified arise from singly ionized species, with lower levels slightly higher than those in the 31 Cyg spectrum.

IUE continued to observe VV Cephei throughout nearly a full orbit, but unfortunately, the aging satellite did not last long enough to follow the system into the next eclipse. However, it did detect some very interesting phenomena. Despite the 20-year orbital period, rapid changes in the out-of-eclipse spectrum were seen on time scales as short as two weeks. In some spectra, the absorption line profiles are symmetric. In most of the spectra, additional absorption is seen on the long-wavelength side of the line profiles, and in a few spectra, additional blue-shifted absorption is seen. The level of the continuum changed, apparently stochastically, by as much as a factor of two. These rapid changes suggest variable accretion on to the hot component. This should not be surprising, as it is moving through the extended

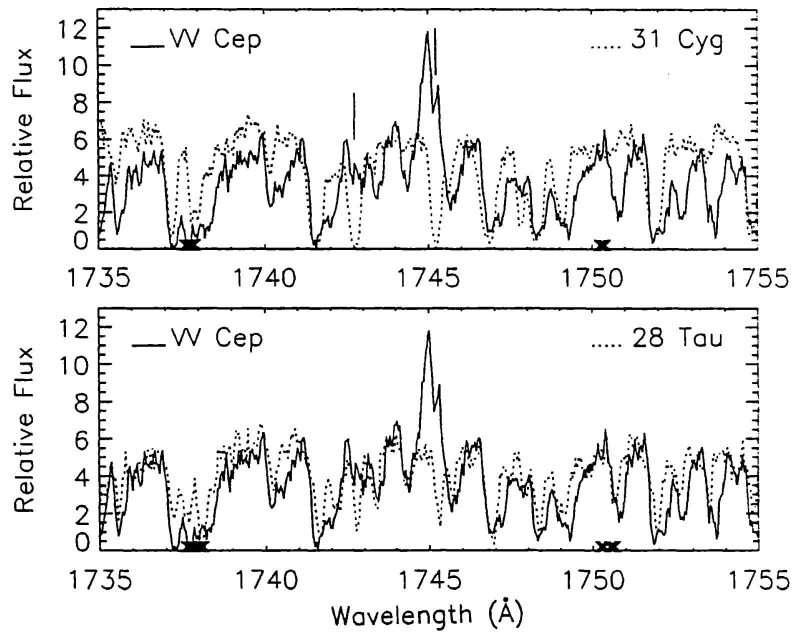

Fig. 1. Upper Panel - comparison of out-of-eclipse spectrum of VV Cep compared with eclipse spectrum of 31 Cyg. Lower Panel - VV Cep and 28 Tau.

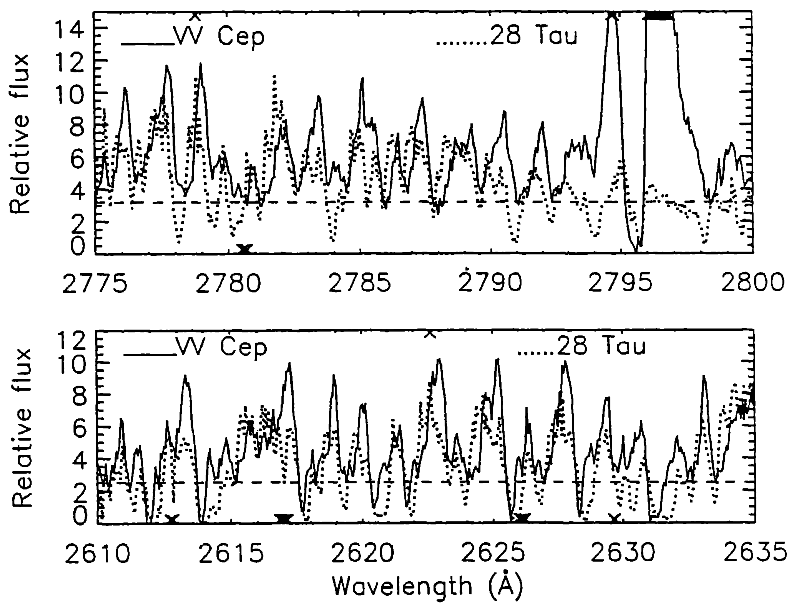

Fig. 2. Two regions of a VV Cep spectrum showing circumstellar envelope lines.

Another intriguing observation made by the IUE was that only a few absorption features approach atmosphere/wind of the M supergiant, which is probably very clumpy.

Another intriguing observation made by IUE was that only a few absorption features approach zero intensity in VV Cep, although many of them do in 28 Tau. The only lines which approach zero intensity in VV Cephei are those which would be expected to form in the circumstellar envelope arising from the M supergiant mass loss, those with lower levels below about 1 eV. Fig. 2 shows two regions of a VV Cep spectrum (taken near third quadrature) which shows these two types of lines. In the upper panel, the only line which penetrates below the dotted line is the circumstellar (and interstellar) absorption component of the Mg II k line. In the lower panel, the lines approaching zero central intensity belong to UV multiplet 1 of Fe II. The lower levels of this multiplet range from 0.0 to 0.12 eV. An interstellar contribution is unlikely for the lines above 0.0 eV so we can be confident that we are observing the M supergiant wind in these features. The non-circumstellar absorption lines show an additional peculiarity. Even when the continuum varies significantly, the flux in the line center remains approximately constant.

My study of the UV spectrum of VV Cephei revealed five distinct line components: a) Emission lines, which are mostly due to various multiplets of Fe II. Many of these are double-peaked, with one component arising from the M supergiant wind and another from material surrounding the hot component. b) Broad absorption lines, including Si IV and Fe III. These arise from the hot component or from material accreting around it. c) Lines which weaken and disappear as the hot star emerges from eclipse. Those thus far identified arise from neutral species. d) Absorption features which show variable line profiles and do not penetrate below a minimum central depth. These lines are called "shell" lines because of their presence in the strong shell spectrum of 28 Tau. e) Narrow absorption features which do not share the profile variations of the shell lines. Many of these do approach zero central intensity, and some are seen as absorption features between the double-peaked emission features. These absorption lines likely arise from the extended M supergiant wind.

A wonderful new opportunity to learn more about this complex spectrum came with the launch of the Hubble Space Telescope (HST). Its 92-inch mirror provides much more light-gathering power than the 18-inch mirror of IUE, and permits ultraviolet spectroscopy at much higher spectral resolution.

I was fortunate to be able to join forces with Dr. Philip Bennett and his colleagues at the University of Colorado. Their research group had successfully competed for time on the HST to observe the Zeta Aurigae systems, and had developed the theoretical framework necessary to interpret the spectra. They wished to extend their work to VV Cephei. So we combined my familiarity with the IUE spectra of VV Cephei with their track record for observing the Zeta Aurigae systems and proposed for observing time on the HST. We did not get time to observe the system prior to ingress into the 1997-8 eclipse, and unfortunately, the most interesting parts of ingress into totality were unobservable because of a servicing mission to the telescope.

Luckily, when we proposed to observe the system during totality and egress from eclipse, we were granted observing time. (It probably did not hurt that the Chair of the Cool Stars Telescope Allocation Committee was none other than Dr. Andrea Dupree of the initial IUE observations!)

Although the first data were obtained in November 1997, we were using a new instrument, and fully calibrated data has just recently become available. The increased resolution can clearly be seen in comparing the Mg II h and k lines as observed with IUE (Fig. 2) with the same features observed with the HST (Fig. 3). In Fig. 3, both the h and k lines are plotted on the same radial velocity scale. Two

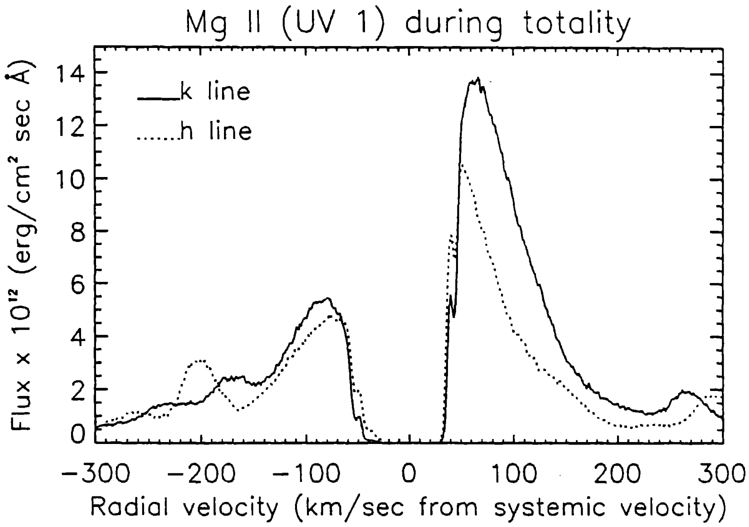

Fig. 3. h and k lines plotted on same radial velocity scale.

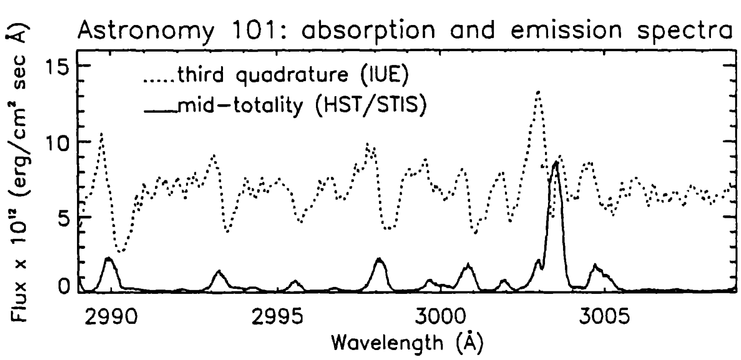

Fig. 4. Absorption and emission spectrum near 3000 Å.

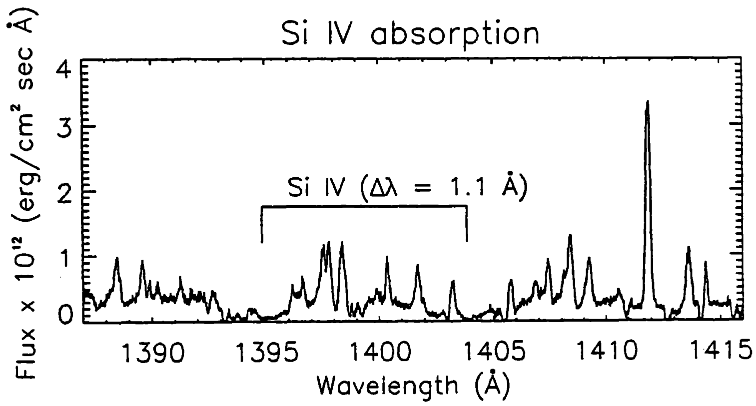

Fig. 5. Si IV absorption.

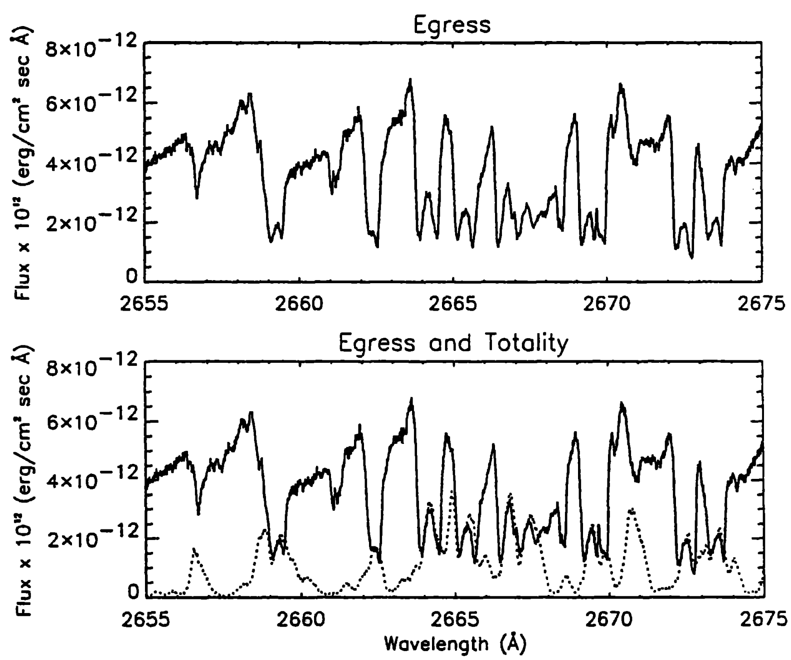

Fig. 6. HST Spectrum of egress (Upper) and compared to totality (Bottom).
but the feature near -50 km/sec must arise in the stellar wind itself.

features appear in the deep circumstellar/interstellar cores of these lines. Their repetition between the two lines strongly supports their reality. The feature near 40 km/sec is probably a geocoronal feature,

The spectrum during totality is as rich with emission lines as the spectrum outside eclipse is rich with absorption features. These emission lines are believed to originate from photons scattered in the extensive circumstellar envelope created by the M supergiant wind. Fig. 4 compares these lines in a region of the spectrum near 3000 Å wavelength. The strongest emission feature seen in this region of the spectrum in totality is an emission line of Fe II (multiplet UV 78). This feature is typical of strong emission lines seen during totality, appearing double-peaked due to a blue-shifted absorption component from the M-supergiant circumstellar envelope which is superimposed on the emission feature. The strong long-wavelength peak of the emission line is seen even outside eclipse; this feature is seen a bit to the red of the HST spectrum in the IUE spectrum plotted in Fig. 4. The stronger emission component in the out-of-eclipse IUE spectrum comes from the material around the hot component.

The other emission lines in the totality spectrum appear single, and in general, the same lines that are seen as shell absorption features out of eclipse appear as emission features. As mentioned above, however, circumstellar absorption features seen out of eclipse remain as absorption features during totality.

At shorter wavelengths, a measurable continuum is seen even during totality. Fig. 5 shows a region of the spectrum near 1400 Å. In this figure, the continuum is most clearly seen near 1415 Å. It rises to shorter wavelengths until absorption from the wings of Lyman alpha sets in at about 1250 Å. The narrow absorption features seen in this region of the spectrum arise from low-lying levels one would expect to see from the M supergiant circumstellar envelope. Lines with higher excitation potential appear in emission, as they do at longer UV wavelengths. There are two broad dips in the continuum which correspond to the broad absorption features of Si IV seen in the out-of-eclipse spectrum. This suggests that the continuum seen during totality arises as the hot component's continuum is scattered by the material in the M star wind.

The observations of the spectrum during totality have begun to answer some of the questions posed by the IUE data. The puzzling lower limit to the depths of the shell lines can be explained because it results from the emission lines of the M supergiant circumstellar envelope.

The upper panel of Fig. 6 shows an HST spectrum taken after the hot star has emerged from total eclipse. The absorption features are complex, with many lines appearing doubled. These line profiles are much more easily understood when the spectrum is compared to that seen during totality in the lower panel. The bottoms of many of the line profiles as seen during egress and outside eclipse are controlled by the underlying emission from the M supergiant's wind.

Without the observations obtained during total eclipse, we were unable to correctly interpret these line profiles. Now we can subtract the emission due to the circumstellar wind from the spectra, which will allow us to better measure the changing absorption as the hot component continues to emerge from eclipse. Our goal is to use this changing absorption to determine the density and temperature structure of the inner regions of the M supergiant wind.