Spectroscopic Monitoring of the 2017–2019 Eclipse of VV Cephei

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Abstract VV Cephei is an M supergiant star that eclipses its B-type companion every 20.36 years. It is the eponymous member of the red supergiant + hot main-sequence binaries known as the VV Cephei stars. The red supergiant primary is surrounded by a circumstellar shell due to mass loss via a slow, stellar wind, and this circumstellar material interacts with the hot companion. Spectroscopic observations in the ultraviolet indicate the presence of material accreting onto the hot star from the wind of the M supergiant primary, and the probable presence of an accretion disk around the companion. The hot star and disk produce a local H II "bubble" that results in very prominent Hα emission originating from the vicinity of the companion. In this work, we report on a continuing campaign of spectroscopic observations of Hα emission from VV Cep over the period 2015–2020 by amateur observers of the ARAS spectroscopy group. We also present a newly discovered 42-day period variability in the equivalent width of this Hα emission.

1. Introduction

VV Cephei (M2 Iab + B0-2 V) is the best known, brightest, and eponymous member of the composite spectrum binaries with M supergiant primary stars and hot B-type main-sequence companions. The M supergiant primary is one of the largest known stars in size, with a radius of about 1000 $R_{\odot}$. Both the M supergiant and its companion are comparably massive, with masses near 20 $M_{\odot}$. The VV Cep binary system is observed nearly edge-on, and undergoes total eclipses every 20.36 years, which is one of the longest known periods of any eclipsing binary. This binary has been a system of particular interest for almost a century, following McLaughlin's (1936) discovery that the binary was eclipsing. It is one of the most massive, longest-period eclipsing binary systems known. McLaughlin (1934) first reported on the composite-spectrum binary, with its broad hydrogen emission lines and H and K lines of ionized calcium (Ca II). Subsequently, McLaughlin (1936) announced that the hot star in VV Cep had been eclipsed, establishing the system as an eclipsing binary. Goedicke (1939) carried out the first detailed spectroscopic analyses of this system. Wright (1970) presented an orbital solution for the M supergiant primary. Hutchings and Wright (1971) and Wright (1977) recognized that the Hα emission came from around the hot companion and used this prominent emission line to derive orbits of the secondary star.

The visible spectrum longward of 5000 Å, except for the very prominent emission line of Hα, is that of the luminous red supergiant primary. However, shortward of 4000 Å, the spectrum of the hot companion becomes increasingly dominant. This system has given its name to the class of similarly massive M supergiant binaries with hot companions: the VV Cephei stars (Cowley 1969). In VV Cep itself, the evolved M supergiant is surrounded by an extensive shell of circumstellar material due to mass lost from the red supergiant via a stellar wind, and this wind completely envelops the companion's orbit. Some of this material is captured by the hot companion, resulting in an accretion region around the B-type star, and emission from this accretion region mostly obscures the photospheric spectrum of the hot star in the ultraviolet. The companion is hot enough, at around spectral type B1 V, to ionize a local "bubble" of circumstellar gas, and it is recombination of ionized hydrogen in this H II region that produces the prominent Hα emission, as well as strong emission in the other hydrogen Balmer lines and in the Balmer continuum in the ultraviolet (see Figure 1). The ultraviolet spectrum is characterized by numerous emission lines of Fe II, which are probably pumped by strong emission in the Lyman-β line (Bauer and Bennett 2000) from the same H II region.

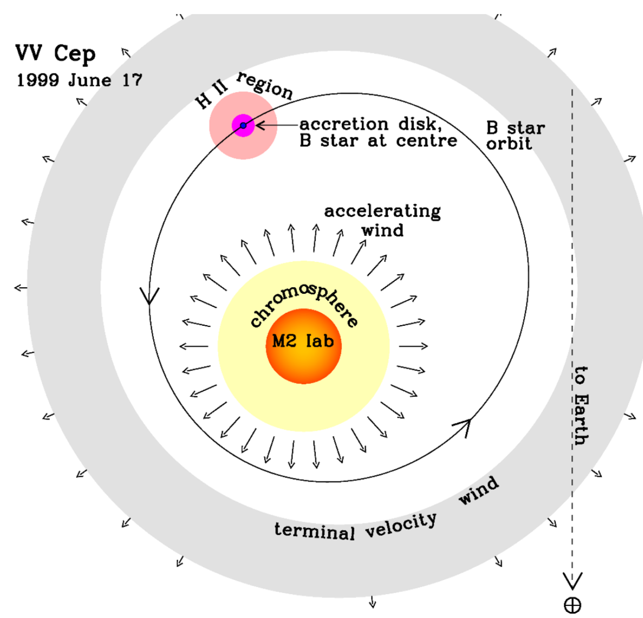

Figure 1. The orbit and structure in the orbital plane of the VV Cephei binary on 1999 June 17, drawn to scale (adapted from Bennett and Bauer 2015).

As noted, out of eclipse, the Hα spectral line at 6563 Å is particularly prominent in this star, with a peak emission flux several times that of the M star's continuum. The Hα line is one of the few features in the visible spectrum that arises from the hot companion, as established by a radial velocity behavior that runs counter to that of the red supergiant. Observations of the Hα emission line provide valuable information on the difficult-to-observe companion, and of a possible accretion disk around the hot companion (Wright 1977; Kawabata *et al.* 1981; Moellenhoff and Schaifers 1978, 1981). Despite the prominent wind accretion and interaction in this binary, direct mass transfer via Roche lobe overflow does not appear to be taking place. The spectroscopic orbit of the M supergiant is fairly well established, and the orbit is decidedly eccentric, with an eccentricity of $e=0.35$ (Wright 1970). The two stars are reasonably well-separated, with a ratio of orbit semi-major axis to M star radius (a/R_1) of about 5, and a periastron separation to M star radius of ~3.3 (Bennett and Bauer 2015). Since mass transfer binaries undergoing Roche lobe overflow invariably have orbits circularized by tidal interactions, the eccentric nature of the VV Cep orbit suggests that VV Cep has never undergone significant episodes of Roche lobe mass transfer.

The ultraviolet spectrum appears to be largely of nonstellar origin, with strong inverse P Cygni line profiles of ionized metal lines (especially Fe II), and a continuum that varies by up to a factor of 3 outside of eclipse. Both the inverse P Cygni profiles—indicative of infalling circumstellar gas—and the variable Balmer emission continuum suggest an accretion source for the nonstellar UV spectrum (Bauer and Bennett 2000; Bennett and Bauer 2015). The spectroscopic orbit (Wright 1977) implies both stars are comparably massive, so the companion must be a luminous main-sequence star, but even so, the stellar source contributes only 30–50% of the UV luminosity. The rest of the luminosity must come from the accretion region, which is probably organized as an accretion disk around the hot star. The nonstellar component of the spectrum in the UV consists of Balmer continuum emission, and metal line emission (especially Fe II) powered by fluorescence with Lyman emission lines. The accretion disk is also hot, and appears to contribute to much of the ionization of neutral circumstellar hydrogen in a local, confined bubble around the hot star (Figure 1).

In this paper, we present an extensive set of high-cadence spectroscopic monitoring of the Hα emission line in VV Cep over the entire eclipse period of nearly three years. This continues the work previously presented by Pollmann, Bennett, and Hopkins (2016) and Pollmann *et al.* (2018). We also report on a newly discovered 42-day oscillation in the equivalent width (EW) and peak fluxes, and a 51-day radial velocity oscillation in the blue (V) component of the double-peaked Hα emission line. We attribute these periodic variations to the precession of the accretion disk around the hot B-type companion.

2. Observations and analysis

Long-term monitoring of the Hα region of the spectrum of VV Cep started in July 1996 (by EP) to observe the 1997–1999 eclipse, and has continued for 24 years to the present day. Since April 2010, observers of the *Astronomical Ring for Access to Spectroscopy (ARAS)* spectroscopy group have been involved in, and contributed substantially to, this long-term monitoring campaign. In 2015, a combined photometric and spectroscopic campaign was organized by J. Hopkins, P. Bennett, and E. Pollmann to monitor the recent 2017–2019 eclipse. This eclipse began (first contact) in continuum light, around the beginning of September 2017, and ended (fourth contact) at the start of April 2019. Over this period, medium-resolution spectroscopic observations were obtained in the red spectral region centered on Hα, using commercially available instrumentation such as the Shelyak Instruments LHires III spectrograph (R ~ 17000) and a CCD detector. We present a summary of the results of this observing program in this paper. In Figure 2, we show a typical LHires III spectrum of VV Cep observed in the red spectral region out of eclipse, with its central self-absorption feature dividing the observed Hα emission profile into characteristic blue and red components. For each spectrum, the total Hα equivalent width (EW), the EW and peak flux of the blue (V) and red (R) components, and radial velocity of the blue (V) emission component were measured. The total Hα EW variation over the entire 24-year observational period (see Figure 3) shows considerable variation outside of eclipse on both long and short timescales. Remarkably, weak, narrow Hα emission remains present even at mid-eclipse, as can be seen from Figure 4. This emission must be coming from spatially extended (and low velocity) regions far enough from the hot star so as to remain visible at mid-eclipse.

The slow Hα EW variation, occurring on decadal timescales (Figure 3, dashed curve), correlates with the orbital separation of the two stars, with the largest emission flux occurring near periastron. We report here on the discovery of a rapid 42-day variability that is also present in the EWs and peak fluxes of both the V and R components. A similar 51-day variability is present in the radial velocity of the V component. Surprisingly, this 42-day variability persists through total eclipse, as can be seen from Figure 5.

The continuous and high-cadence nature of these Hα observations allows the time-variation of the Hα red (R) and the blue (V) emission components to be analyzed in unprecedented detail. In principle, a detailed analysis of the Hα profile over the course of the eclipse should permit the geometry of the Hα emitting region to be determined. For this work, we simply present the results and an analysis of the period of the EW and the peak fluxes of the Hα V and R emission components and the radial velocity (RV) variation of the V emission component, and defer that complete analysis to a future work. Figure 6 shows the behavior of the EW and peak fluxes for the V and R components over the course of the eclipse. In particular, the asymmetric nature of the V/R eclipse curve, with its minimum occurring well prior to mid-eclipse, implies that the eclipse of the V component of the Hα emission during ingress proceeds much more quickly than that of the R component.

The AVE code of Barbera (1998) was used to carry out the PDM analysis. Results of this period analysis of the Hα emission line EW and of the peak flux of both V and R components of nearly 1000 spectra indicate a significant period of about 42 days. This 42-day period variation is shown in Figure 7 for the

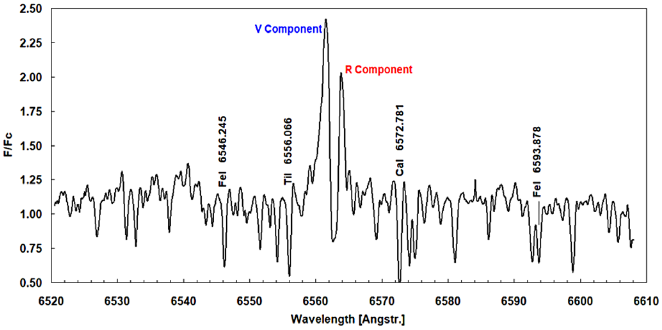

Figure 2. Typical out-of-eclipse spectrum of VV Cep showing double-peaked Hα emission.

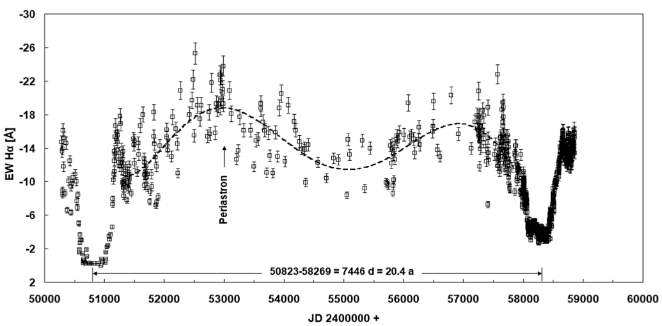

Figure 3. Hα equivalent width (EW) from 1996 to 2020.

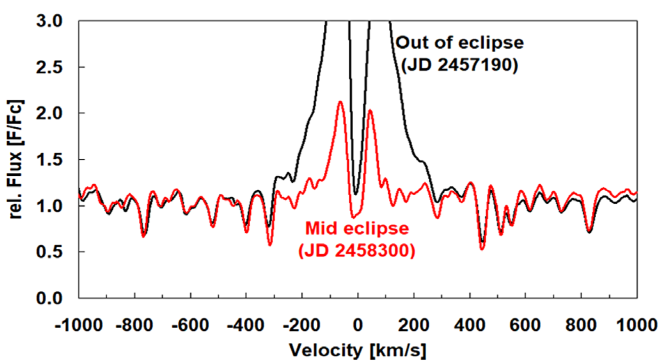

Figure 4. The narrow Hα profile during totality implies the emission here comes from a low velocity region extending beyond the occulting M supergiant, compared to the much broader out-of-eclipse profiles from the accretion disk. Only about 25% of the total flux comes from this extended region.

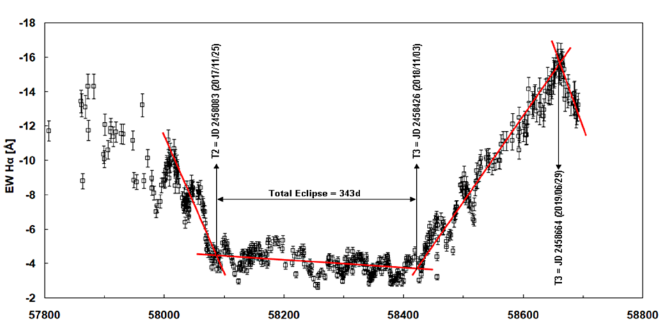

Figure 5. Hα emission EW for the 2017–2019 eclipse. The 42-day variability persists through totality.

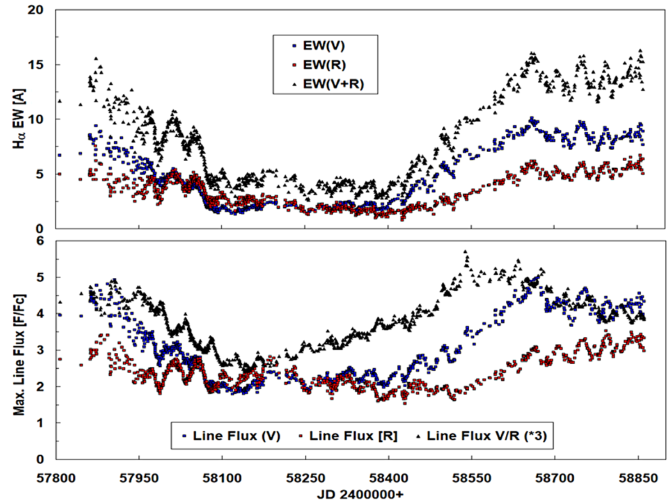

Figure 6. VV Cep Hα EWs and fluxes of blue (V) and red (R) emission peaks during the 2017–2019 eclipse.

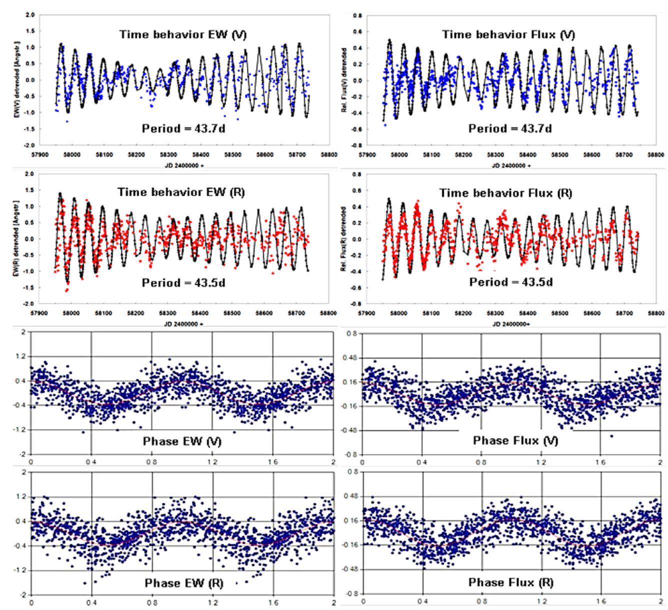

Figure 7. Periodic variability of EW (left) and peak line flux (right). Both periods are ~42 days

EW of the V and R components (left panels), as well as for the peak flux (right panels) of both emission components.

The 42-day variability is confirmed by a periodogram of the V/R ratio, shown in Figure 8. The source of the observed Hα variability is probably precession of the accretion disk. Although presumably oriented perpendicular to the hot star's rotation axis, this accretion disk need not lie exactly in the orbital plane of the binary. In this situation, the M supergiant would exert a torque on the accretion disk, accounting for the observed precession.

This variability resembles the 58-day semi-regular variability reported by Baldinelli *et al.* (1979), who obtained non-standard R-band photometry (using 103aE plates + RG1 filter) of VV Cep from 1976 to 1978. However, the Hα variability described here would seem to be an order of magnitude too small in amplitude to produce the ~0.1-magnitude variation in R flux seen by Baldinelli *et al* (1979).

A precessing accretion disk rotation axis with a period of 42 days should result in a similar radial velocity variability. Analysis of more than 400 medium-resolution spectra of VV Cep obtained from 2018 January to 2020 January confirms a similar short periodic variability in the radial velocity of the Hα V component. However, a period analysis (see Figure 9) of the velocity residuals (after subtraction of a smooth trend) gives a period of 51 days instead, but with relatively little power in this period, which only accounts for about one-third of the amplitude of the total short period variability.

Note that the radial velocity measurements were carried out with respect to the M supergiant reference frame. Variation in the width of the central absorption near eclipse might also alias the derived V component radial velocities. In any case, the radial velocity time series analysed here is relatively short. We will revisit the radial velocity analysis after more data have been obtained, and after carrying out a proper subtraction of the orbital solution first.

3. A proposed model

As summarized in the introduction, recombination of ionized hydrogen (H^+) in an H II region around the hot star and the accretion disk in VV Cep produces the observed Hα emission peak. The Hα emission profile is broadened by the high velocities present in the infalling gas, as well as from gas in the accretion disk rapidly orbiting the hot star. The low velocity wind enveloping the entire binary star system results in absorption at velocities near the center of the Hα line profile, resulting in a characteristic double-peaked emission profile with separate blue (V) and red (R) emission components.

The spectroscopic orbit implies the hot companion is also a massive star, and that must be (from its mass, and position on the main sequence) an early B star, probably of spectral class B0-2 V. It is difficult to be more precise because the UV spectrum is non-stellar. Moreover, the hot companion is not a compact object in the usual sense. Therefore, it is unlikely that gravitational accretion is the source of the energy powering the non-stellar UV source. The nature of the nonstellar luminosity (hydrogen Balmer and Lyman line emission, and Balmer continuum emission) is that of a recombination spectrum. This suggests the non-stellar emission is being powered by the local ionization of circumstellar hydrogen by the extreme ultraviolet (EUV) radiation field (i.e., at wavelengths shortward of 912 Å) of the hot companion star, with some contribution from the hot gas accreting around the companion star. In this scenario, the EUV continuum of the hot star and accretion region is being reprocessed into hydrogen recombination emission. This process, which depends on the local circumstellar hydrogen density and accretion disk orientation, is what we propose to cause the variable nature of the UV spectrum of VV Cep.

The size of the B star and its accretion disk, which together produce the UV continuum, are small compared to the M supergiant. We know this because the UV light curve drops quickly to zero during total eclipse, implying that the UV continuum flux comes from a small emitting volume, consistent with a hot star surrounded by a compact accretion disk source. But about 20–25% of the Hα flux remains present even at

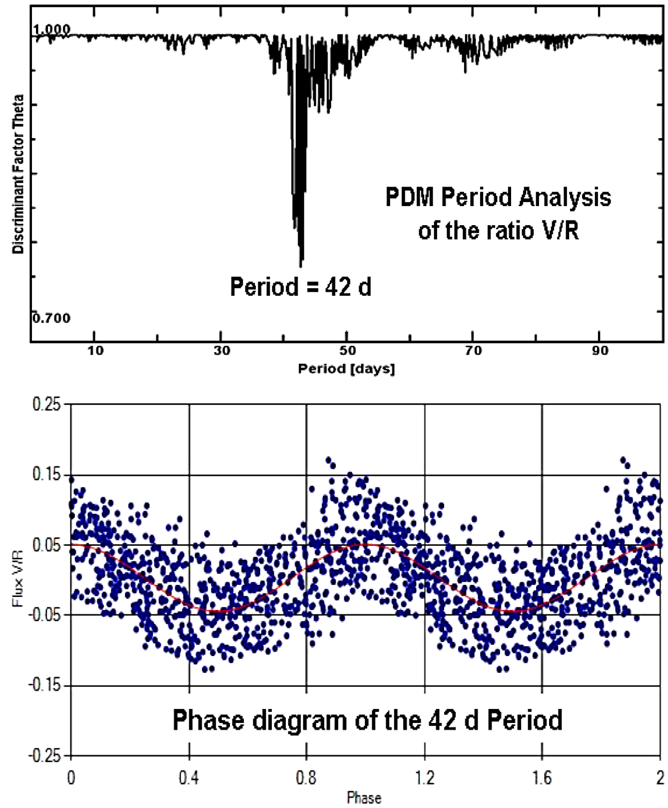

Figure 8. V/R period analysis. Top: PDM periodogram. Bottom: V/R values phased to 42-day period.

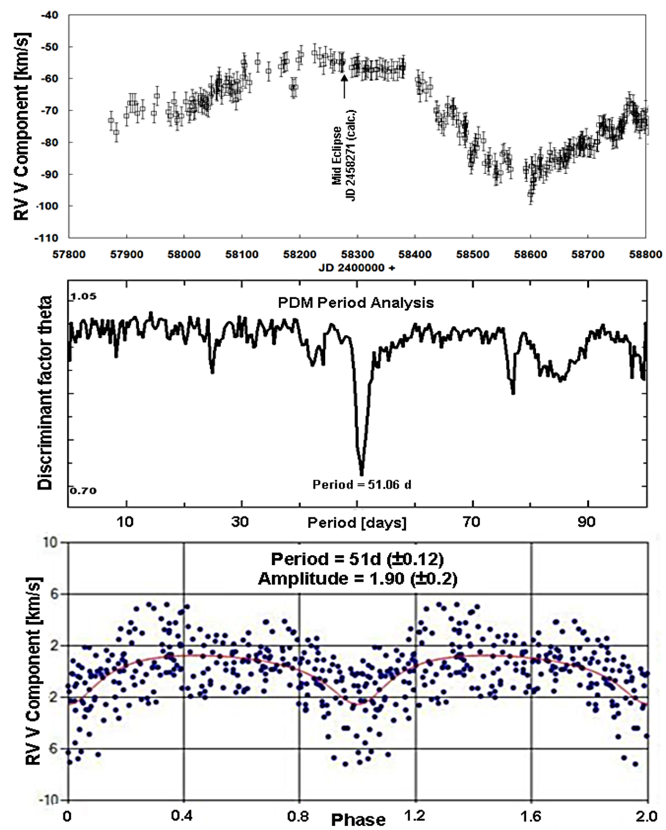

Figure 9. Radial velocity analysis of the V component of the Hα emission. Top: radial velocity of the Hα V component. Middle: Period analysis of the detrended data. Bottom: Phase plot of the radial velocity time series for the derived 51-day period.

mid-eclipse, so that some of this emission must come from an extended region on the sky that is larger than the projected disk of the M supergiant. A more detailed analysis of the evolution of the Hα profile during the eclipse now underway should provide valuable constraints on the size and structure of the emitting volume.

The observed 42-day period of Hα variability is typical of Be star disk precession periods (Schaefer *et al.* 2010) and it is tempting to suspect that mechanism (precession of the accretion disk) also causes the Hα variability in VV Cep, with its accretion disk. But the situation is more complicated than this because the accretion region in VV Cep is totally eclipsed for 19 months during totality. This behavior imposes a severe constraint on the process responsible for the variability. The rapidity of the 42-day variability implies this occurs on small physical scales. This is because a region undergoing a coherent variation cannot be larger than the distance over which the physical disturbance responsible for the variability propagates during the period of the variation. But for the variability to remain present during total eclipse, when the hot star and its accretion disk are totally eclipsed, requires that the precessing disk be communicating that information to a region outside the eclipsed volume. Since typical wind velocities in VV Cep, away from the immediate vicinity of the hot star, are $\sim 20\,\mathrm{km\,s^{-1}}$, wind travel times to cross an M star diameter ($\sim 1000\,R_\odot$) are about a year, or much longer than 42 days. The orbital velocities of both stars are of comparable speeds: $\sim 20\,\mathrm{km\,s^{-1}}$. There is no evidence of higher velocity flows on large scales in VV Cep. Therefore, the source of the variation cannot be gas flows or winds originating with the accretion disk—the velocities are just too slow.

This leaves radiation as the only obvious mechanism fast enough to propagate the 42-day variability over a region larger than that of the M supergiant's radius. The light travel time to cross the M supergiant radius ($\sim 1000\,R_\odot$) is less than an hour. The propagating radiation cannot be Hα directly because $n=2$ level populations of H I are insufficient to scatter Hα light in the relatively cool circumstellar gas around VV Cep. Instead, we propose that extreme UV (EUV) radiation emitted by the accretion disk and hot star ionizes neutral hydrogen gas in two lobes directed above and below the plane of the accretion disk (Figure 10). Observations of VV Cep in the ultraviolet with the Hubble Space Telescope (Bauer, Gull, and Bennett 2008) demonstrated the existence of spatially extended emission in strong lines of Fe II. These prominent ultraviolet emission lines are excited by Lyman-β emission from the same recombination process into the hydrogen $n=3$ level that produces the observed Hα emission.

In this model, it is the geometry of the H II region emission lobes, varying with the precession of the accretion disk, that gives rise to the 42-day Hα variability. As the disk precesses, these cones of ionization sweep through the neutral circumstellar wind in VV Cep much like a searchlight beam. Inside each H II lobe, circumstellar neutral hydrogen is ionized to H^+ by the disk's EUV radiation, and then recombines to produce Hα and higher Balmer line emission. The precession of the disk results in a modulation of the strength, and radial velocity, of the resulting Hα emission, which depends on the geometry of the bipolar emission cones relative to the stellar wind and the

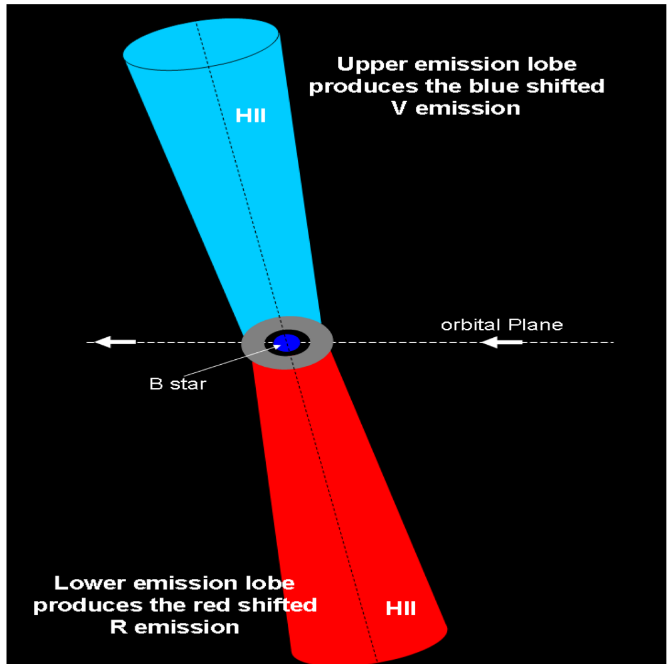

Figure 10. Model of two Hα emission lobes extending above and below the orbital plane from the precessing accretion disk.

position of the eclipsing supergiant. Out of eclipse, Hα emission from the H II region near the precessing accretion source is also observed directly. This model accounts for the continued presence of the 42-day Hα emission flux variability during total eclipse.

The Hα emission lobes are not exactly perpendicular to, but are obliquely inclined, to our line of sight due to the $i \approx 80°$ inclination of the orbital plane of VV Cep. The blue-shifted (V) emission comes from the lobe which opens towards the observer, while the red-shifted (R) emission comes from the lobe opening away from the observer. In addition, the blue V lobe must be more occulted by the red supergiant than the R lobe at the start of the eclipse, because the V lobe fluxes decline more steeply at eclipse ingress. We require this geometry to explain the asymmetric nature of the V and R curves. Further, the significantly narrower profile shape of the Hα emission during total eclipse (seen as red curve in Figure 4) implies a lower velocity source far from the accretion disc, confirming that not all the Hα emission comes from the immediate vicinity of the accretion disc.

4. Conclusions

We present medium-resolution ($R \sim 17000$), high cadence observations of the Hα emission line in VV Cep, observed by members of the *ARAS* group from 2010 to the present, and report the discovery of a rapid 42-day variability that is present in the EWs and peak fluxes of both the V and R components. A similar 51-day variability is present in the radial velocity of the V component. Surprisingly, this variability persists through total eclipse, when the hot companion star and surrounding accretion region are totally eclipsed.

To explain the continuation of the 42-day variability through total eclipse, we propose a model in which lobes of neutral hydrogen gas are ionized by extreme ultraviolet radiation from a precessing accretion disk around the hot companion star in this massive binary system. Recombination from the resulting H II region produces the observed Balmer continuum and line emission, including the prominent Hα emission. As the accretion disk precesses with its 42-day period, the H II ionization lobes directed away from the disk sweep through the circumstellar gas around the M supergiant, producing the observed periodic variability in Hα fluxes and radial velocity, even when the accretion region itself is eclipsed.

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