MASS DETERMINATION AND DETECTION OF THE ONSET OF CHROMOSPHERIC ACTIVITY FOR THE SUBSTELLAR OBJECT IN EF ERI DANI

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ABSTRACT

EF Eri is a magnetic cataclysmic variable that has been in a low accretion state for the past 9 yr. Low-state optical spectra reveal the underlying Zeeman-split white dwarf absorption lines. These features are used to determine a value of 13–14 MG as the white dwarf field strength. Recently, 5–7 yr into the low state, Balmer and other emission lines have appeared in the optical. An analysis of the Hα emission line yields the first radial velocity solution for EF Eri, leading to a spectroscopic ephemeris for the binary and, using the best available white dwarf mass of 0.6 M☉, a mass estimate for the secondary of 0.055 M☉. For a white dwarf mass of 0.95 M☉, the average for magnetic white dwarfs, the secondary mass increases to 0.087 M☉. At EF Eri’s orbital period of 81 minutes, this higher mass secondary could not be a normal star and still fit within the Roche lobe. The source of the Balmer and other emission lines is confirmed to be from the substellar secondary, and we argue that it is due to stellar activity. We compare EF Eri’s emission-line spectrum and activity behavior to that recently observed in AM Her and VV Pup and attributed to stellar activity. We explore observations and models originally developed for V471 Tau, for the RS CVn binaries, and for extrasolar planets. We conclude that irradiation of the secondary in EF Eri and similar systems is unlikely and, in polars, the magnetic field interaction between the two stars (with a possible tidal component) is a probable mechanism that would concentrate chromospheric activity on the secondary near the substellar point of the white dwarf.

Subject headings: stars: activity — stars: individual (EF Eridani, AM Herculis, VV Puppis) — stars: low-mass, brown dwarfs

1. INTRODUCTION

EF Eridani has become a binary star of renewed interest in recent years. This is primarily due to the fact that the mass accretion from the low-mass secondary to the highly magnetic white dwarf has been essentially stopped for the past 9 yr. During this period of very low accretion, observers have flocked to telescopes around the world, with the hope of detecting and understanding the component stars that make up EF Eri. As we will see, it has taken a small 1.5 m telescope, part of the Small and Moderate Aperture Research Telescope System (SMARTS) consortium, to provide the first new insights into the true nature of this fascinating (and confounding) binary.

EF Eri was discovered over 30 years ago as a hard X-ray source (2A 0311−227; Cooke et al. 1978). It was quickly identified optically as a 14th magnitude blue source (Griffiths et al. 1979) with properties similar to AM Herculis (Charles & Mason 1979). AM Her, the not-so-typical prototype of the AM Herculis class of interacting binaries, was the first member of a new class of cataclysmic variable (Tapia 1977). Today, these magnetic cataclysmic variable (CV) binary systems are called polars (due to their polarized light), and we argue that it is due to stellar activity. We compare EF Eri’s emission-line spectrum and activity behavior to that recently observed in AM Her and VV Pup and attributed to stellar activity. We explore observations and models originally developed for V471 Tau, for the RS CVn binaries, and for extrasolar planets. We conclude that irradiation of the secondary in EF Eri and similar systems is unlikely and, in polars, the magnetic field interaction between the two stars (with a possible tidal component) is a probable mechanism that would concentrate chromospheric activity on the secondary near the substellar point of the white dwarf.

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series, and other spectral lines, are also now present. Detailed analysis of the Hα emission line yields the first dynamical orbital velocity solution for EF Eri. We use this information and the remaining spectral features to determine the source of the emission and show that it is consistent with chromospheric activity on the substellar secondary.

2. OBSERVATIONS

We present a number of observations from a variety of sources in this paper. The largest data set is from our monitoring program of EF Eri using the SMARTS telescopes at the Cerro Tololo Inter-American Observatory (CTIO). These observations consist of multicolor photometry and optical spectroscopy covering the Hα region. We also present a single blue spectrum obtained in the fall of 2005 at the Apache Point Observatory (APO) and use it to compare EF Eri to the prototype polar, AM Her. The comparison reveals that both stars have white dwarfs with similar magnetic field strengths, and both stars show stellar activity indicators during their low state. Finally, we present a high-S/N, low-state optical spectrum from Keck II, revealing the full panorama of ongoing spectral activity in EF Eri.

2.1. SMARTS

Photometric and spectroscopic monitoring of EF Eri has been accomplished using the SMARTS7 facilities at Cerro Tololo. This program has operated from 2003 August to the present, and all data were obtained by the SMARTS service observers.

2.1.1. Photometry

The optical images were obtained using A Novel Double-imaging Camera (ANDICAM) dual channel imager on the SMARTS 1.3 m telescope. ANDICAM obtains simultaneous optical and near-IR images, although EF Eri is too faint in its low state for us to make use of the near-IR capability. The optical detector is a Fairchild 447 2048 × 2048 CCD. We obtained 100 s integrations through the B, V, and I filters. The images are processed (overscan subtraction and flat fielding) prior to distribution to SMARTS observers. Because we obtained only single images through each filter each night, the noise is dominated, in some cases, by cosmic rays and hot pixels.

We obtained 90 sets of useful images between 2003 August 22 and 2005 December 21. On 2005 November 2 UT we obtained continuous coverage of 1.09 orbital cycles in 36 V-band images between 2.34 and 3.81 hr UT (see § 2.1.2).

We measured the star’s brightness using differential photometry with a 4′′ radius aperture. The photometry is differential with respect to five nearby stars. One of these stars appears to be a long-term variable that has faded by about 0.06 mag in I compared to five nearby stars. One of these stars appears to be a weak-lined, late-type star (see § 2.1.2). The RC spectrograph is a slit spectrograph with a 300′′ long slit oriented east-west and a Loral 1200 × 800 CCD detector. We made all our observations through a 110 μm (1′) slit. EF Eri has a nearby unrelated companion star approximately 22′′ west-southwest. In order to interpret the SMARTS observers with our field and to make completely sure we did not intersperse or include spectra of this nearby object, we purposefully obtained a spectrum of this star. This companion star appears to be a weak-lined, late-type star (∼K) and has absolutely no spectral similarities to EF Eri: no emission lines, significantly brighter,9 and easily avoided in the spectrograph slit.

We obtained at least three spectral images at each epoch in order to filter cosmic rays. The basic spectral reductions subtract the overscan and divide each image by the normalized flat-field image using a pipeline written in IDL. The spectrum in Figure 2 and Figure 3 shows simultaneous photometry and covers the entire optical spectrum out to 0.9300 Å. All subsequent spectra were obtained with gratings 47 in first order, with a wavelength range of 5652–6972 Å and a resolution of 3.1 Å. Wavelength calibration uses a neon lamp exposure, taken at the start of the observing sequence. Exposure times for the individual frames range from 500 to 1200 s. We generated a median image from all the images at each of the 10 epochs. As these longer exposure times caused the spectral signal to be integrated over a significant fraction of the 81 minute orbital period, any radial velocity or line profile information is smeared in the summed images. Figure 3 shows simultaneous photometry by S. Leggett and T. Geballe. Upon reduction, these images showed EF Eri to have a K magnitude of 15.2 ± 0.2, the same value it has had for the past 8 yr.

Figure 10 compares the Figure 1a observations on the EF Eri orbital period of 81 minutes and our new spectroscopic ephemeris discussed below. The sinelike shape of the B light curve, with semiamplitude near 0.1 mag, is similar to but less well defined than in V and appears to be absent altogether in I. These light-curve features show the same level, shape, and phasing as light curves presented in Harrison et al. (2003; see Fig. 2 shows observations obtained in 2001 December).8 Similar to the Harrison et al. interpretation, we believe the weak blue photometric modulation is due to a surface feature on the white dwarf. We discuss below (§ 3.3) whether this feature is consistent with a bright, warm region or a cooler, higher opacity region near one of the accretion poles.

2.1.2. Spectroscopy

Our first two SMARTS spectra of EF Eri were obtained on 2004 August 13 and 2004 October 19 UT. The two spectra look nearly identical, and the second one is presented in Figure 2. These spectra were obtained with the 1.5 m SMARTS telescope using grating 13 providing 17 Å spectral resolution and covering most of the optical (3200–9500 Å). We note in Figure 2 (as well as in the August 13 observation) the clear signature of the two Balmer lines in emission (Hα equivalent width is −19 Å; see § 3.3). He i emission at 5876 Å, and the probable detection of the underlying Zeeman-split absorption lines from the magnetic white dwarf.

Given our detection of Balmer emission, we continued monitoring EF Eri, ultimately obtaining 10 sets of spectra with the RC spectrograph on the 1.5 m SMARTS telescope starting on 2004 October 20 UT (see Table 1). The RC spectrograph is a slit spectrograph with a 300′′ long slit oriented east-west and a Loral 1200 × 800 CCD detector. We made all our observations through a 110 μm (1′) slit. EF Eri has a nearby unrelated companion star approximately 22′′ west-southwest. In order to orient the SMARTS observers with our field and to make completely sure we did not intersperse or include spectra of this nearby object, we purposefully obtained a spectrum of this star. This companion star appears to be a weak-lined, late-type star (∼K) and has absolutely no spectral similarities to EF Eri: no emission lines, significantly brighter,9 and easily avoided in the spectrograph slit.

8 Note that Harrison et al. phased their light curves on the original Bailey photometric ephemeris.

Note that in the familiar finding chart for EF Eri available from the Downes CV Atlas at http://archive.stsci.edu/legelmelcvat/ and other places, the nearby companion star and EF Eri appear similar in brightness. This image was obtained at a time when EF Eri was in a high (bright) state near ν = 14.
and spectroscopy for EF Eri. These observations provide unambiguous evidence of the relationship between the $\text{H}$/$\text{C}_1$ velocities and the $\text{V}$-band light curve.

EF Eri is a challenging target for spectroscopic work at a 1.5 m telescope. The SMARTS service observers are quite skilled and highly proficient, and performed the spectral observations with great care. The SMARTS spectra of EF Eri on all occasions present a weak (pseudo-)continuum, with a typical $\text{S/N}$ per pixel in the continuum $<3$. We extract the spectra from the images in two ways. First, we use a boxcar extraction with an extraction...
width set by a fit to the cross section of the spectrum at chip center. The background is measured above and below the spectrum and linearly interpolated to the position of the source spectrum. Second, we fit a Gaussian atop a flat background at each column in the chip. In both cases, the location of the spectrum (the trace) is determined from a bright star observed that night, and shifted to match the position of the target. The width of the spectrum as a function of wavelength is determined from the trace of the bright star. The extraction width is not allowed to vary in the Gaussian fit. The flux from the Gaussian extraction is the analytical integration of the Gaussian fit.

We observed a spectrophotometric standard, either Feige 110 or LTT 4364, each night in order to convert the counts spectrum to a flux spectrum. Due to seeing-related slit losses, we do not obtain absolute fluxes, but rather use the standards to recover the shape of the continuum.

We know that the Balmer emission produced by the high-state accretion in EF Eri greatly declined after the start of its 1997 January low state (Wheatley & Ramsay 1998; Beuermann et al. 2000). Spectra obtained in 2000 November (Reinsch et al. 2004; Euchner et al. 2002) show very weak Balmer emission, with only H\textalpha{} being above the continuum. By 2001 March, the Balmer emission had disappeared altogether (Harrison et al. 2003\textsuperscript{10}) and remained absent as late as 2002 August (Harrison et al. 2004b; Howell 2004). On 2004 August 13 UT, we noted the presence of Balmer and He emission in EF Eri and thus began our SMARTS monitoring efforts. Therefore, we can only state that the H\textalpha{} emission in EF Eri started sometime between 2002 August and 2004 August.

While our spectra are too poor for continuum flux measurements, in nearly all of them H\textalpha{} emission was clearly seen, and we could obtain a measurement of its line center and equivalent width. To accomplish this, we Fourier-smoothed the individual spectra (see Fig. 4) and then fit the spectra between 6400 and width set by a fit to the cross section of the spectrum at chip center. The background is measured above and below the spectrum and linearly interpolated to the position of the source spectrum. Second, we fit a Gaussian atop a flat background at each column in the chip. In both cases, the location of the spectrum (the trace) is determined from a bright star observed that night, and shifted to match the position of the target. The width of the spectrum as a function of wavelength is determined from the trace of the bright star. The extraction width is not allowed to vary in the Gaussian fit. The flux from the Gaussian extraction is the analytical integration of the Gaussian fit.

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\textsuperscript{10} In Fig. 4 of Harrison et al. (2003), the authors claim that the H\textbeta{} emission line has weakened. A reexamination of this spectrum with respect to the pure Zeeman absorption spectrum observed in 2002, as well as model fits such as in Reinsch et al. (2004), show that it is likely that no Balmer emission was present in the Harrison et al. spectrum.
6700Å with the sum of a quadratic background and a Gaussian line. The S/N of the (pseudo-)continuum in our data is far too low to reveal any photospheric features from the white dwarf. The Hα/C11 emission line is generally narrow, but can be significantly velocity-smeared even in a 10 minute integration. We use the best-fit position of the Gaussian for the radial velocity analysis. A simple centroid of the emission line gives comparable results. Figure 5 shows one of the trailed SMARTS spectra of the Hα/C11 emission line in EF Eri. The plot illustrates the obvious sinusoidal motion of the Hα emission line, as well as its modulation with phase.

2.2. Apache Point Observatory

Optical spectroscopy of EF Eri and AM Her was obtained on 2005 November 6 UT using the Double Imaging Spectrograph on the APO 3.5 m. We used the high-resolution gratings with a 1.5" slit to deliver a dispersion of 0.6Å pixel⁻¹. The central wavelength of the blue spectrum was 4500Å, covering the spectral range λ3865–5094. The exposure times for both AM Her and EF Eri were 20 minutes each; this is one-fourth of the EF Eri orbital period. The exposures were started at 6:21:56.0 2005 November 6 (EF Eri) and 1:18:30.4 2005 November 6 UT (AM Her). Both AM Her and EF Eri were in a low state during this time (see Kafka et al. 2005, 2006).

Figure 6 presents our APO observations of EF Eri and AM Her. The spectrum of AM Her has been overplotted at a flux level about 10 times below its real value. In Figure 6, we note that the spectrum of AM Her rises to the blue while EF Eri drops, a consequence of the difference of the white dwarf temperatures in the two polars. Balmer, Ca ii (H and K), and He i emission are seen in both systems and have been associated with the secondary star in AM Her.

2.3. Keck

On 2006 January 3 UT a 10 minute, medium-resolution spectrum of EF Eri was obtained with the Echelette Spectrograph and Imager (ESI; Sheinis et al. 2002) in echelle mode on the Keck II telescope. This setup provided a useful spectral coverage of 4000–10,000Å in 10 spectral orders with a constant dispersion.

**Table 1—Continued**

| HJD of Mid-exposure | Exposure Time (s) | Spectroscopic Phase* | Hα Center (Å) |
|---------------------|-------------------|----------------------|---------------|
| 2,453,579.90220.....| 500               | 0.3564453            | 6569.764      |
| 2,453,620.72200.....| 1200              | 0.9091797            | 6557.291      |
| 2,453,620.73610.....| 1200              | 0.1597900            | 6569.510      |
| 2,453,620.75020.....| 1200              | 0.4104004            | 6568.200      |
| 2,453,621.75840.....| 1200              | 0.2648926            | 6569.407      |
| 2,453,621.76890.....| 1200              | 0.5155028            | 6566.310      |
| 2,453,621.78300.....| 1200              | 0.7661133            | 6556.565      |
| 2,453,635.73010.....| 1200              | 0.6446533            | 6562.242      |
| 2,453,689.63210.....| 600               | 0.5705872            | 6563.307      |

* Determined using the new spectroscopic ephemeris given herein. Phase 0.0 equals the time of primary (white dwarf) red-to-blue crossing, which equals the time of secondary inferior conjunction. Spectroscopic phase 0.0 = Bailey et al. (1992) photometric phase 0.41.

**Fig. 3.**—Radial velocity of the Hα emission line and the simultaneous V-band photometry from SMARTS on 2005 November 3. The radial velocities are from a Gaussian fit of the emission feature; the uncertainties represent ±1 Å systematic uncertainty due to velocity smearing and the skewing due to a nonflat underlying continuum. This shows the relation between the photometric orbital modulation of the white dwarf and the orbital location of the secondary.

**Fig. 4.**—Representative SMARTS spectra of EF Eri. The top three spectra are single 10 minute exposures, while the bottom spectrum is their sum. The vertical dotted line represents the rest velocity of Hα. Fluxes for each spectrum are on the same scale, but are offset by one unit from the previous spectrum. Compare these observations with the Keck spectrum of EF Eri (Fig. 9) and you will see that the SMARTS data allow us to measure the top of the Hα profile.

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**Fig. 5.**—Trailed spectrum of EF Eri for the observations obtained on 2006 February 4. The slightly jumpy nature of the Hα emission line is mainly due to limited phase sampling of the ultrashort 81 minute binary orbit. Changes in the line strength are due to small seeing variations but also have a real component, as discussed in the text (see Fig. 9). The data are not smoothed, and the bright spot near phase 0.8 at ~6700Å is a cosmic ray.

11 See http://www.apo.nmsu.edu/Instruments/DIS/Default.html.
of 11.4 km s\(^{-1}\) pixel\(^{-1}\). A slit width of 1" aligned along the parallactic angle was used with a plate scale of 0.127–0.183 pixel\(^{-1}\) providing a resolution of 3000–5000 across the optical spectrum, giving 1.68 resolution at H\(_\alpha\). Wavelength calibrations were accomplished using Hg-Ne-Xe and Cu-Ar lamps. The active flexure control on ESI minimizes drift in the wavelength calibration and/or any fringing that is crucial for clean sky subtraction. The spectrophotometric standard Feige 110 was used for flux calibration. The data were reduced using standard IRAF routines with additional custom analysis routines to properly correct for the large curvature, strong nonlinear photometric response, and small tilt of sky lines.

Figure 7 shows our high-S/N Keck spectrum of EF Eri. The underlying white dwarf continuum is now revealed, presenting the Zeeman-split Balmer absorptions from the white dwarf. Figure 7 also shows the presence of narrow emission lines of the entire Balmer series of hydrogen, the Pickering series of He\(_i\) (4388, 4471, 4922, 5876, 6678, and 7065 Å), Na\(_i\), and the Ca\(_{\text{ii}}\) triplet (8498, 8542, and 8662 Å). No He\(_\alpha\) emission is observed. The continuum slope change seen near 8600 Å, also noted by Beuermann et al. (2000), is not a contribution from the secondary but, as shown by Harrison et al. (2003, 2004b), may be due to a weak cyclotron hump feature consistent with the 13–14 MG magnetic field present in EF Eri (see § 3.2). Our high-S/N Keck spectrum and our low-resolution SMARTS spectrum (Fig. 4) confirm our belief that the SMARTS radial velocity data sample only the top of the H\(_\alpha\) emission line sitting on a pseudo-continuum.

3. ANALYSIS

3.1. Radial Velocity Solution

The SMARTS spectral observations can be discussed as two groups. The first group (group one) is data specifically obtained for radial velocity and orbital motion determination. They all have a uniform integration time and were collected over a short time period in 2005 November, 2005 December (two separate nights), and 2006 February. The remaining SMARTS spectra (group two) consist of our monitoring observations obtained between 2004 October and 2005 November (see Table 1). The four data sets that form group one cover at least one orbital period each in a continuous manner. Group two consists of spectra usually taken in threes
Our best-fit sine curve solution to the Hα emission line centers for all our spectra yields a normal CV spectroscopic primary star red-to-blue crossing ephemeris for EF Eri of

\[ T_0 = 2.453.716.61108(5) \text{ HJD} + 0.05626586(80)E, \]

where orbital phase 0.0 is the secondary’s inferior conjunction. We have assumed that the orbit is circular and that the components make their respective red-to-blue crossings 180° apart in phase and have used the orbital period determined by Bailey et al. (1982). Our best fit to the Hα measurements yields a \( K_2 \)

\[ 269 \pm 18 \] and \( \gamma = 115 \pm 15 \text{ km s}^{-1}. \] Spectrophotometric phase 0.0 (0.5) is equal to Bailey et al. photometric phase 0.41 (0.91). Note that all other plots in the paper use our new spectroscopic orbital phasing derived above.

The large value for \( K_2 \) indicates that the emission is produced on or near the secondary, given its large value. It would be impossible for the white dwarf in this binary to have such a large \( K \) amplitude. We show below that this emission, as appears true for both AM Her and VV Pup during their low states, is not caused by irradiation. Given our new dynamic orbital solution, the suggestion that the narrow photometric dip feature used by Bailey et al. to define phase 0.0 is caused by some sort of gas-stream eclipse by the secondary cannot be correct.

### 3.2. Zeeman Absorption Spectroscopy and Cyclotron Emission

The nearly identical Zeeman absorption structures from the white dwarfs in both AM Her and EF Eri are easily seen in Figure 6. AM Her has a listed magnetic field strength of 12.5 MG (Bonnet-Bidaud et al. 2000), while EF Eri’s field strength has been estimated in various ways to be between 17 and 35 MG (Warner 1995; Reinsch et al. 2004). Using Figure 2 in Harrison et al. (2004b) and our Keck spectrum presented here (Fig. 7), we can measure the Zeeman-split \( \pm \sigma \) components in the Hα line to determine the surface magnetic field strength in EF Eri. We find that the \( \pm \sigma \) components are split from the main component of Hα by 280 \( \pm 14 \) Å in both the old spectrum and our new Keck observation. Using equation (10) in Wickramasinghe & Ferrario (2000) for the linear regime, this splitting yields a surface field strength of 13.8 \( \pm 1 \) MG for the white dwarf in EF Eri. We can also match our Figure 7 Hβ profile in some detail to the model work presented in Figure 2 of Euchner et al. (2005). Doing so yields a best magnetic field estimate of 13–14 MG. A rough comparison of our Hα and Hβ \( \pm \sigma \) profiles with the detailed modeling for single, highly magnetic white dwarfs presented in Euchner et al. (2005, 2006) shows that we can estimate the linear Zeeman surface field to about \( \pm 1 \) MG, but can do no better with these data.

Using our new spectroscopic phasing for EF Eri, we note that the optical light curve (Fig. 1) shows an asymmetric humplike modulation consistent with a slight brightening (0.1 mag) centered near phase 0.4. The amplitude of this hump increases toward the blue. Phase 0.4 is where we would expect to be viewing the magnetic white dwarf at near right angles to the magnetic poles, thereby suggesting that the slight flux increase may be related to cyclotron emission. Although EF Eri is in a low accretion state, it is not zero, as cyclotron humps—consistent with a 13–14 MG field—are seen in infrared spectra (Harrison et al. 2004b). The low-state light curve could also be interpreted as having a luminosity dip from 0.8 to 0.0. This phase is where we would expect to have a more or less direct view of the main accretion pole on the white dwarf and/or the back end of the secondary. Given that the amplitude of the light curve increases to the blue, a cooler secondary back end seems to be ruled out. Perhaps we are seeing a dark spot on the white dwarf near the main accretion pole due to a region...
of higher opacity caused by atmospheric metals migrating toward the magnetic pole and forming a metallic lake (as seen in the single white dwarf GD 394; Dupuis et al. 2000). This idea, however, is difficult to reconcile given the high-UV flux levels observed in EF Eri in recent Galaxy Evolution Explorer (GALEX) observations (Szkody et al. 2006). Weak mass accretion appears to be a common behavior in low-state polars (e.g., Pandel & Cordova 2005; Howell et al. 2006a) and is likely due to connected magnetic field lines between the two stars, allowing the secondary wind (flares, prominences, etc.) to be accreted onto the white dwarf (see below).

3.3. The Origin of the Optical Emission Lines

It is useful to compare the current spectrum of EF Eri to the low-state spectra of AM Her and VV Pup. All three show emission from H $\alpha$ and Ca ii. While He i emission is clearly seen in VV Pup (Mason et al. 2006) and AM Her (Kafka et al. 2006), it is only confidently detected in our Keck spectrum of EF Eri. AM Her ($P_{\text{orb}} = 3$ hr, M4 V secondary) has been in a low state much of the past 2 yr, and Kafka et al. (2005, 2006) attributed the low-state Balmer emission observed in AM Her to stellar activity on the secondary star. Their claim is based on a detailed examination of the Balmer emission, particularly H$\alpha$, including its radial velocity amplitude, its narrowness, and the line-strength behavior throughout the orbit. Their analysis eliminates irradiation as the dominant source for the Balmer emission seen in AM Her during the low state. VV Pup ($P_{\text{orb}} = 100$ minutes), with an M7 V secondary star, has also been in a low state for much of the past few years, and the origin of its emission-line spectrum has also been attributed to stellar activity on the secondary star (Mason et al. 2006). Both AM Her and VV Pup seem to show secondary star emission features at all times during their recent low states. EF Eri’s secondary, however, appears to not have had line emission for the first ~5–7 yr of its low state. If the onset of the emission lines in EF Eri corresponds to the start of a stellar activity cycle, as we believe, this event did not cause EF Eri to immediately go into a high state. The activity in AM Her and VV Pup also seems to be uncorrelated with their high/low states starting or stopping. Thus, there does not appear to be a simple one-to-one correspondence between start/stop of stellar activity and high-/low-state transition in polars.

Our radial velocity curve makes it clear that the H$\alpha$ emission in EF Eri comes from the secondary, but its source and the source of the Balmer, Na i, and Ca ii H and K emission is an open question. Irradiation and stellar activity are the two obvious choices for the cause.

3.3.1. Irradiation or Stellar Activity?

While irradiation is seen in close interacting binaries, we know of no process whereby the cool white dwarf in EF Eri could suddenly start irradiating the secondary without any evidence for a change in the accretion rate. We also note that AM Her and VV Pup in their recent low states show no indication of irradiation induced or enhanced Balmer or other emission, even given their hotter white dwarfs (see §4). However, Kafka et al. (2006) concluded that it is possible that some low-level irradiation may be present in AM Her during the low state, but it is difficult to disentangle it from the much stronger activity-induced emission.

Balmer, Na i, Ca ii (H and K and the IR triplet), and He i emission are all the usual signatures of stellar activity (Giampapa et al. 1978), as these lines form in the high photosphere/low chromosphere of the stellar atmosphere (see Vernazza et al. 1973). It has always been suspected that the secondary stars in CVs should be highly active, as they are rapidly rotating. However, there is little direct observational evidence of this assumption, except in the polars during low states (e.g., Schwwope et al. 2001).

Figure 9 presents the equivalent width (EW) of the H$\alpha$ line from our group 1 SMARTS spectra phased on the orbital period. We present the data for each night using a different color, the same scheme as in Figure 8. If the H$\alpha$ line were produced by irradiation, we would expect the EW to be strongly peaked with a maximum near spectroscopic phase 0.5 (the white dwarf facing the secondary side of the star), a result inconsistent with the measurements. What we see in Figure 9 instead is a nearly constant EW value, albeit slightly variable, and a possibly reduced but non-zero line width near phase 0.0, the back side of the secondary. As in AM Her and VV Pup, we find that the emission, and probably the stellar activity processes, are generally concentrated toward the white dwarf-facing side of the secondary. A stronger magnetic field on the white dwarf and/or the alignment of active regions on the secondary star with the magnetic field (Simon et al. 1980) may cause a stronger “front side” concentration of activity.

In addition, a tidal coupling model presented in Rottler et al. (2002) as a cause of white dwarf–facing activity concentration will certainly be active in polars (and all CVs) and may help, or be the primary cause, of a longitudinal enhancement.

The concentration of stellar activity and star spots on the secondary, at or near L1, has been previously assumed in the literature. For example, Hessman et al. (2000) presented a model to explain the high-/low-state behavior in AM Her. They used the modulated mass-transfer levels in this polar as an indicator of the amount of star spots needed near L1. They concluded that nearly one-half of the “L1 region” of the secondary star would have to be covered with spots during a high state. Furthermore, Hessman et al. determined that this “L1 area concentration” could only be possible if the spots were somehow forced to wander into the region, possibly by a cyclic $\alpha^2$-$\Omega$ dynamo.12 While this extreme

12 Note that in CVs with orbital periods below the period gap, the secondary stars are believed to have internal structures (fully convective or brown dwarf-like, e.g., VV Pup and EF Eri, respectively), which are not expected to operate the $\alpha^2$-$\Omega$ dynamo in the same manner, or at all, compared with CV secondary stars above the period gap (e.g., AM Her).
level of star spot coverage has not been observed in AM Her or other polars during a high state, it is easily hidden by the much higher accretion luminosity.

While the EW of the Hα emission above the (pseudo-)continuum is relatively constant over all phases for a given orbit of EF Eri, there is evidence for long-term changes of up to a factor of 2. Figure 10 presents the long-term variations in the Hα emission-line EW. The EW values have been integrated over each set of observations, or at least half the orbital period, so they should not be affected by motions of the line across the underlying white dwarf Zeeman-split absorption. Assuming that the white dwarf continuum is not varying, and there is no substantial accretion, the observed variations in Hα must be intrinsic to the secondary, probably the typical variations of active regions and star spots as observed in single active stars.

3.3.2. He i and Ca ii Emission

He i emission is a useful tool for the determination of the physical conditions in which it is produced. The He i line at 5876 Å is a triplet, while that at 6678 Å is a singlet. Three mechanisms populate these states: (1) recombination to an excited state after photoionization by λ < 504 Å photons, (2) collisional excitation from the He i ground state, and (3) excitation of the singlets only by resonance scattering. This latter option is easily eliminated here, as we detect both singlets and triplets in emission. Following the discussion related to the active M star AD Leo (Giammapa et al. 1978; Schneeberger et al. 1979), it is shown that the $I(5876 \text{ Å})/I(6678 \text{ Å})$ ratio can be as high as 45 in quiescent prominences in the Sun, but is near 3.3 in active prominences. This latter value is near the ratio of the triplet-to-singlet statistical weights (3.0).

The $I(5876 \text{ Å})/I(6678 \text{ Å})$ ratio of 45 has been explained (Heasley et al. 1974) as a natural consequence of a typical quiet photosphere in a solar-like star. At cool temperatures (<8000 K), the He i resonance-line photons, which populate the singlet levels, cannot penetrate as far as the λ < 504 Å photons that populate the triplet levels. As the temperature increases, i.e., moving into an active stellar atmosphere, the $I(5876 \text{ Å})/I(6678 \text{ Å})$ ratio gets quickly reduced, almost independent of density, as collisional excitation from the ground state and collisional coupling of the triplet-singlet levels bring the two populations into closer accord. During low states, polars are not strong X-ray sources, and even in high states, the X-ray emission is primarily produced at the white dwarf magnetic pole accretion region(s). We can conclude that the excitation of the secondary He i lines, during a low state, is not likely to be due to a strong <504 Å continuum, as needed for option (1) in the previous paragraph. Further evidence of the lack of X-ray-induced lines is provided by the absence of He ii or other high-excitation emission lines in the optical spectra. Using the EF Eri spectra presented in Figure 7, we can measure the $I(5876 \text{ Å})/I(6678 \text{ Å})$ line ratio. We find $I(5876 \text{ Å})/I(6678 \text{ Å}) = 3.7$, a value expected for He i emission by collisional excitation in chromospheres hotter than 8000 K. Athay (1965) provided rough guidelines for this sort of line-emitting region yielding column densities of $\sim 10^{18}$ cm$^{-2}$ at temperatures of 20,000 K or hotter.

The Ca ii IR triplet, in emission in EF Eri, has peak fluxes in the ratio 1:2.6:2 for the 8498, 8592, and 8662 Å lines, respectively. This is comparable to the flux ratio observed in a wide variety of objects from CVs (Persson 1988) to pre-main-sequence stars (Hamann & Persson 1992) to active chromospheres in DMe stars (Pettersen 1989). The lines in the CVs are fairly broad, exhibit disk profiles, and form in the accretion disks; any weaker, narrower secondary emission is hidden. The DMe stars show narrow emission reversals in their Ca ii photospheric absorption lines. The pre-main-sequence stars show both broad and narrow components. The broad component seems to arise in a turbulent region near the base of the wind, while the narrow component is at rest with respect to the star, and may form in the chromosphere. In EF Eri the triplet lines are broadened by about 150 km s$^{-1}$, which is somewhat larger than but comparable to the expected ~100 km s$^{-1}$ $v\sin i$ of the secondary. We suspect an origin in the chromosphere of the secondary.

Given the above discussion, we conclude that the most likely source of the line emission detected from the secondary in EF Eri is due to stellar activity. We have observed that in EF Eri, compared with AM Her and VV Pup, there were no secondary emission lines during the first 5–7 yr or so of the low state, but the emission began during the extended low state and has been present for the past 1.5 yr. This discovery argues for the fact that we have observed the onset of a stellar activity cycle in the substellar companion star in EF Eri.

3.4. The Component Masses

The white dwarf in EF Eri has been observed during the current low state by a few observers (e.g., Beuermann et al. 2000; Howell 2004) who found it to be cool, near 9500 K, and each made some attempt to determine its mass. Beuermann et al. (2000) provided the most rigorous determination for the mass of the white dwarf and concluded that the most likely value is near 0.6 $M_\odot$. This value, equal to the mean mass for white dwarfs found in CVs, has been generally used by the community for EF Eri. Harrison et al. (2003) fit optical and IR photometry of EF Eri in the low state and found that an 0.6 $M_\odot$ white dwarf worked quite well in the overall spectral energy distribution for EF Eri and led to an estimated distance of 90 pc, a value in agreement with the determination by Beuermann et al.

A recent paper by Wickramasinghe & Ferrario (2005), as well as older works by Liebert et al. (2003a) and Liebert (1988), have shown that the masses for isolated magnetic white dwarfs are, on average, higher than nonmagnetic white dwarfs. The mean masses of the two groups are 0.93 and 0.57 $M_\odot$, respectively. However, in CVs the mean white dwarf mass seems to be near 0.6 $M_\odot$ regardless of magnetic or nonmagnetic (Warner 1995). Shylaja (2004) presented a compilation of derived masses for the white dwarfs in EF Eri.

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13 We can easily separate out the weaker Na emission sitting near the He 5876 Å line.
magnetic CVs and found a trend toward higher mass (average near 0.85 $M_\odot$), but lower mass magnetic white dwarfs (0.4–0.6 $M_\odot$) constitute about 1/4 of the sample. For now, we adopt the value of 0.6 $M_\odot$ for the mass of the magnetic white dwarf in EF Eri but examine the consequences of it having a higher mass later on. Using the relationship between the size of the secondary star Roche lobe and the binary mass ratio $q (M_2/M_1)$ and assuming that the secondary object, regardless of its true nature, is centrally condensed, we have
\[
\frac{R_2}{a} = 0.462 \left( \frac{q}{1 + q} \right)
\]
(Paczynski 1971; Huber et al. 1998). The secondary Roche lobe size ($R_2$) for EF Eri is $\sim 0.1 R_\odot \sim R_J$ or $7 \times 10^7$ m (Howell et al. 2001), and the mean separation of the two stars, $a$, is $3.5 \times 10^8$ m (Howell 2004). Substituting these values in the above equation yields a mass ratio of $q = 0.992$ for EF Eri. Taking the white dwarf mass to be $0.6 M_\odot$, we find $M_2 = 0.055 M_\odot$. If the cut-off for core energy generation via hydrogen burning is taken as 0.06 $M_\odot$, then the secondary in EF Eri is substellar and the binary may be a postperiod minimum system (Howell et al. 2001). However, we should keep in mind the use of a “best guess” white dwarf mass and that our determined value for $M_2$, within errors, is essentially at the stellar/substellar mass boundary.

Taking the above masses at face value, our measured $K_1$ would predict a $K_1$ amplitude for the white dwarf of 25 km s$^{-1}$, a value that will be extremely difficult to measure for the $V = 18.5$ white dwarf in EF Eri, especially given that its Balmer absorption lines are Zeeman split and their relative location and shape will probably change throughout the orbit as the effective observed magnetic field strength changes. Of course, any precise $K_1$ measurement attempt could only be performed during a low state.

Beuermann et al. (2000) limited the secondary star in EF Eri to be later than M9 based on its nondetection in the red optical spectral region, and Howell & Ciardi (2001) used a moderately good S/N K-band spectrum to set a secondary mass limit of $< 0.05 M_\odot$. Using their spectral energy distribution, Harrison et al. (2003) concluded that the secondary in EF Eri is near L5, a result that remained in agreement with the secondary’s continued nondetection in K-band spectra (Harrison et al. 2004b). Finally, Howell et al. (2006b) have used *Spitzer Space Telescope* observations of EF Eri in the 3–8 $\mu$m region to further set a limit on the secondary, finding that it is consistent with an object approximating a very late L- or T-type brown dwarf. All of these limits and mass estimates for the secondary in EF Eri seem to be in approximate agreement, generally independent of an assumed white dwarf mass. They all seem to indicate an $M_2$ value near 0.05–0.055 $M_\odot$. This mass for $M_2$ is also in agreement with the theoretical expectations for the secondary star in a CV such as EF Eri, based on its orbital period and the assumption of the standard CV evolution model (Kolb & Baraffe 1999; Howell et al. 2001; Politano 2004).

If the white dwarf in EF Eri has a higher mass, say as high as the average value for single magnetic white dwarfs, 0.95 $M_\odot$, then $M_2$ would have a mass near 0.087 $M_\odot$, assuming $q$ remains the same. While we cannot completely rule out this value for the mass of $M_2$, such a star would not fit inside the secondary Roche Lobe if it were a normal main-sequence object. Therefore, at this mass, we would expect the secondary to be a dense He core with a thin hydrogen envelope, an object far less likely to show us what appears to be the typical signatures of an active chromosphere.

4. DISCUSSION

4.1. Low States

Today, we know that most polars, including EF Eri, AM Her, and VV Pup have extended low states lasting years and that, in general, most polars show long-term low states and/or spend much of their time in low states (Gerke et al. [2006] and references therein). It is believed that all CVs (polars, dwarf novae, etc.) should have low states but that we only notice them in polars due to their lack of an accretion disk. In CVs with disks, if the mass transfer stops, the optical light may not show a significant dimming, as the optical light is dominated by or has a large contribution from the accretion disk. The stoppage of mass transfer in a nonmagnetic CV may not be easily noted, and if mass transfer restarts within a short time period ($\sim 2–4$ weeks), the entire event might escape detection. King & Cannizzo (1998) provided a theoretical framework for this idea and explored possible observational ramifications that could result. They concluded that current observations do not agree with their predictions of how a disk system would react to a stoppage of mass transfer. Given their work and the fact that polars often show extended low states, it is hard to reconcile the idea that CVs with accretion disks (i.e., the nonmagnetic white dwarf CVs) have low states similar to polars. The VY Scl stars may be the exception, as we discuss below.

It has been argued that the low states are a result of stellar activity cycles on the secondary star, in particular, star spots migrating to the L1 region and stopping mass transfer for some period of time. The idea that “solar cycles” and star spots cause low states has been around for decades. Van Buren & Young (1985) suggested that changes in radius of the magnetically active secondary in RS CVn systems drove the observed orbital period variations. The basic idea is that, during a stellar activity cycle, the magnetic pressure due to the enhanced subsurface magnetic fields displace gas, resulting in a fractionally larger stellar radius. The change in the moment of inertia drives the system out of synchronous rotation, and tidal torques then quickly bring the system back into synchrony. In the case of the RS CVn secondaries, the fractional change in the orbital periods ($\sim 10^{-4}$) requires a similar fractional change in the stellar radius. Applegate & Patterson (1987) applied this type of model to the CVs and predicted that there should be periodic $O - C$ variations on the magnetic activity period of the secondary. These magnetic activity periods are observed to be of order a decade long, within a factor of 2 of the length of the solar cycle.

In the case of the polars, it may be this fractional change in the stellar radius that comes into play. Since the secondary is filling its Roche lobe when in the high state, a small reduction in the stellar radius as the magnetic activity wanes may lead to a cessation of the accretion. The implication is that as the magnetic activity picks up, the star should then expand and eventually accretion should resume. This seems consistent with what we observed in the EF Eri secondary: the magnetic activity was at a minimum when the accretion ceased, and then increased prior to the start of the current high state.

The few direct observational results we do have that reveal stellar activity are all from polars in low states. We have seen that EF Eri entered a low state, and its secondary was inactive, it turned on, and EF Eri stayed in a low state for another 1.5 yr. On the other hand, AM Her and VV Pup, with normal active M star secondaries, went into low states (recently, twice each) and from

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14 Taking $R_2$ as equal to the Roche lobe radius implies that the secondary star fills the Roche lobe. During a low state this may or may not be a valid assumption (see Howell et al. 2000; Howell 2005).
start to end during the low state the secondary was active, at a constant level, throughout. Single active M stars display spectroscopic activity indicators almost all the time, but when they go into flaring or superactive episodes, their chromospheres can expand locally and eject material. This idea of active chromospheric expansion driving L1 mass loss was proposed by Howell et al. (2000) as the possible cause of high/low states. The model removed the need for a star spot at L1 but still kept the idea that stellar activity/flaring somehow triggers state changes. If some magnetic cycle connection is invoked to drive mass flows, then it may be that even in a high state, the photosphere need not fill its Roche lobe. The evidence for star spots at L1 and/or stellar activity directly starting and stopping high/low states seems not to exist.

Assuming, for the moment, that nonmagnetic CVs do not undergo low states, can we explain such a phenomenon? Polar secondaries have been shown to be normal main-sequence stars (Harrison et al. 2005a) while dwarf nova secondary stars to date, at least for systems above the period gap, have been shown to have spectra that reveal odd abundance patterns and are consistent with CNO-processed material. Evidence has been presented that argues for a divergence in the evolutionary history of polars and nonmagnetic CVs (see Schmidt et al. 2005b; Harrison et al. 2005a). If the secondaries in nonmagnetic CVs are in fact remnant He cores from a past time when they were more massive, as has been suggested by Beuermann et al. (1998), Howell (2005), and Harrison et al. (2005a), possibly evolving from Algol, then maybe normal stellar activity is not possible. If high/low states are somehow related to activity cycles on the mass donor, this idea may provide a natural explanation as to why dwarf novae and other nonmagnetic CVs do not have polar-like low states.

Having said this, we must consider the VY Sc1 type of CV. These systems are believed to have nonmagnetic white dwarfs and accretion disks, yet they show low-state behavior that may be similar to that seen in polars. VY Sc1 stars have been used as “proof” of star spots and stellar activity, but to date, this is more speculation than anything else. This subclass of CV lies in the 3–4 hr period range, directly above the period gap. Howell et al. (2001) suggested that these stars behave as they do because their secondaries are far from thermal equilibrium and mass transfer can be highly modulated by thermal timescale changes caused by mass loss. If this is true or not is yet to be seen, but observations of the secondary in VY Sc1 stars are likely to offer important clues as to the cause of high/low states.

4.2. Related Binaries

What does the secondary star do in terms of its activity cycles before, during, and after high/low-state transitions? We have seen that stellar activity (as indicated by the usual optical emission lines) may be a constant feature in the normal M star secondaries of polars (i.e., VV Pup and AM Her) and that it can “turn on” during a low state (or at other times?) in at least one substellar mass object: the secondary in EF Eri. Let us examine a few other binary systems in which magnetic fields and stellar activity play important roles. These objects may provide valuable clues toward our understanding of polars.

4.2.1. RS CVn Binaries

Low-mass stars in close binaries exhibit enhanced activity, which is generally attributed to the amplification of the magnetic dynamo by tidally enforced rapid rotation. The activity is generally saturated, with activity-related emission at the level of $10^{-2}$ to $10^{-3}$ of the bolometric flux. The secondaries of polars have similarly rapid rotation and, if magnetic dynamo processes are present, they may also be expected to exhibit activity at the saturated levels. However, the analogy is not exact, as the polar secondaries may have lost a significant fraction of their convective zones, which will affect their ability to maintain or amplify a magnetic dynamo.

Stellar magnetic field emergence is known to be concentrated at certain active longitudes, in both the Sun and more active stars. The active RS CVn binaries are characterized by a “photometric wave,” interpreted as a spotted (and magnetically active) hemisphere that migrates around one of the stars with respect to the binary phase with a period of order a decade. The stars are tidally locked in such close binary systems; the migration is interpreted to represent differential rotation of the star, as the star spots migrate equatorward as they do during a solar cycle. While there is evidence for such a photometric wave with a 6–9 month period in the pre-CV V471 Tau system (Ibanoglu et al. 1994), there is also evidence that the chromospheric Hα is enhanced near the substellar longitudes (Rottler et al. 2002). Because the strength of the emission decreased with time, Rottler et al. dismissed irradiation as the cause and suggested that there is a permanent active longitude at the substellar point, caused by tidal distortion of the convective dynamo. It is not clear whether this is in conflict with the observed wave migration (see § 4.2.2).

There is spectroscopic evidence for enhanced flaring activity at the substellar longitudes in the RS CVn system UX Arietis (Simon et al. 1980), and photometric evidence for enhanced flaring activity at the substellar longitudes in the close binary dMe system YY Gem (Doyle & Mathioudakis 1990). This is presumably attributable to recombination between the extended magnetic loops of the two stars, as in the models by Uchida & Sakurai (1985; see Fig. 11). There is no evidence addressing the long-term variability of the flaring rates. If the recombination involves largescale loops with sizes of order the binary separation, then flaring rates may remain more or less constant, but the rates may be enhanced when the active longitudes coincide with the substellar point.

Eclipse-mapping observations of RS CVn systems, Algol, and YY Gem have been brought to bear on the question of the presence of magnetic connections between stars, as might be expected if the substellar magnetic activity enhancement is indeed permanent. Prés et al. (1995) and Siarkowski et al. (1996) modeled X-ray eclipse observations of the RS CVn systems TY Pyx and AR Lac, respectively. They concluded that in both cases a significant fraction of the emission arises between the stars, in magnetic loops connecting the stars. However, their unconstrained maximum entropy modeling solutions are not unique, and other equally good solutions without interstellar emission exist (see the review by Güdel 2004).

4.2.2. V471 Tau

For V471 Tau, often used as the prototype pre-CV, the hot white dwarf ($T = 35,000$ K) was originally thought to irradiate the K secondary star. The evidence for this was Hα emission from the secondary star, which was observed to be concentrated toward the white dwarf with an EW that peaked near orbital phase 0.5, and the emission line disappeared completely when looking at the back side of the secondary. However, multiyear observations of V471 Tau by Rottler et al. (1998, 2002) showed that in 1987, the Hα emission was consistent with an irradiation interpretation, while in 1990 the emission was much weaker and heavily concentrated toward the white dwarf and in 1992 the emission was completely absent. The (nonmagnetic) white dwarf in V471 Tau was observed to be constant throughout this entire 5 yr period, showing that the secondary star emission was not due to...
irradiation by the hot white dwarf. Rottler et al. believe that their observations are consistent with a “solar cycle”–like change that occurred in the K star.

Given their result with V471 Tau, Rottler et al. (2002) (re)examined a number of similar white dwarf plus red dwarf (WD+RD) systems, all of which were supposed to show irradiation-induced emission from the noninteracting secondary star. Of the 10 hot white dwarf \( (T = 30,000–60,000 \, \text{K}) \) plus red dwarf stars, only one (NN Ser, a WD+RD pair with \( T_{\text{WD}} = 55,000 \, \text{K} \) ) is probably a true case of irradiation. The others are shown to have not enough UV flux to cause irradiation, and the variable H\(_\alpha\) emission was consistent with activity-induced emission lines. Using a model based on the number of \(<912 \, \text{Å} \) photons available for irradiation of the secondary, they show that an incident UV flux at the surface of the secondary star of \( \leq 1 \times 10^{10} \, \text{ergs s}^{-1} \, \text{cm}^{-2} \, \text{sr}^{-1} \) is not sufficient to produce irradiation-induced emission lines. This value exceeds that present in EF Eri from its cooler but closer white dwarf \( (F_{\text{UV}} \sim 1 \times 10^{9} \, \text{ergs s}^{-1} \, \text{cm}^{-2} \, \text{sr}^{-1}) \) and, in fact, it exceeds nearly every CV when not in outburst.

4.2.3. SDSS J121209.31+013627.7

It is interesting to note here the discovery of an object that is very similar to EF Eri in the low state, SDSS J121209.31+013627.7 (hereafter J1212; Schmidt et al. 2005a). These authors discuss this 90 minute, cool \( (T \sim 10,000 \, \text{K}) \), orbitally synchronized magnetic \( (7–13 \, \text{MG}) \) white dwarf binary and present optical spectroscopy closely approximating those of EF Eri in a low state. They conclude, however, that J1212’s H\(_\alpha\) emission is most likely due to irradiation of the probable brown dwarf secondary based on a single-epoch set of phase-resolved optical spectroscopy. The H\(_\alpha\) emission completely disappears when viewing the back end of the secondary star, a similar result to that observed once in V471 Tau. We therefore can ask, given the nearly similar nature of J1212 and EF Eri, if the secondary in J1212 is irradiated, why is the secondary in EF Eri not irradiated? With stellar activity seemingly being concentrated on the secondary at the substellar point of the white dwarf, we will need to be careful in our observational interpretation of any detected emission from the secondary. Radiatively heated atmospheres (irradiation) and active stellar chromospheres (star spots, etc.) may be hard to distinguish. If a star is irradiated, the apparent spectral type (photospheric temperature) should vary as the star rotates. Active chromospheres do fill in lines, which mimics an earlier spectral type in the K stars, but the veiling is wavelength-dependent. In M stars, the veiling might give a spectral type earlier than \( T_{\text{eff}} \), since molecular band strengths are increasing with decreasing \( T_{\text{eff}} \). Realistic, three-dimensional, magnetohydrodynamic models of the secondary star and its magnetic, tidal, and radiative interaction with the primary are needed to fully understand the observations. J1212 and EF Eri are good starting points to use as proxies for our understanding of irradiation, stellar activity on brown dwarf–like secondary stars, and exoplanet physics. With no mass transfer currently underway in J1212, this system is an ideal candidate for multiepoch observations to monitor and detail the nature of the secondary star emission lines.

4.2.4. Extrasolar Planets

The analogy between polars and the magnetically active binary systems is imperfect. In none of these cases does the active star fill its Roche lobe, in none of these cases does the strength of the photospheric magnetic field exceed a few kG, and in none of these cases is the secondary star bathed in a strong external magnetic field. The tidal forces are also much stronger in EF Eri than even in V471 Tau, where the period is 8 times longer and the mass of the cool star is over an order of magnitude larger. A better analogy may be between a star and a planet.

Perhaps the answer to starting and stopping mass transfer lies in the area of magnetic (re)connection between the white dwarf and the secondary star. It was observed (Shkolnik et al. 2003) that for “hot Jupiter”–type extrasolar planets, the host star Ca \( H \) and K emission lines are sometimes modulated on the orbital
Fig. 12.—IRTF SPEX spectra of the highly active stars RS CVn (left) and HD 28867S (right). RS CVn, a short-period active binary system, presents an example of a contrast issue, as the giant companion’s photosphere fills in the activity-induced emission in the near-IR (i.e., Ca II triplets), but we do observe a weak He 10830 Å emission line. In HD 28867S, an M2 pre-main-sequence star (Walter et al. 2003), we again see a He 10830 Å emission line, but with a P Cygni profile. The emission is at zero velocity; the absorption is likely due to accretion in this young star. H i Paschen γ is weakly in emission, with an EW of ~0.4 Å. The Ca II IR triplet is in absorption. While both stars show strong Ca II H and K, and Hα emission in the optical, their infrared spectra do not contain a similar wealth of strong emission lines generated by stellar magnetic activity at temperatures of 6000–20,000 K. This is due both to contrast against a bright photosphere near the peak of the Planck function and to the depth of the IR line formation in stellar atmospheres.

period of the planet. A model proposed by Ip et al. (2004) explains this phenomenon as an interaction of the exoplanet magnetosphere with that of the parent star, in which a magnetic flux loop reconnects using the nearby planet as a conductor. In a polar, which has a much stronger field, it seems obvious that magnetic reconnection and closed field loops would have to pass through the secondary. This idea may also explain why the onset of stellar activity alone is not the direct cause of high/low states and why polars in low states seem to have a residual amount of mass transfer, probably magnetically connected secondary star wind accretion.

A possible observation of magnetic reconnection and closed field loops in the region near L1 but between the two stars (as illustrated in Fig. 11) was noted by Kafka et al. (2005, 2006) in their low-state observations of stellar activity in AM Her. The Hα emission-line profile is triple peaked and leads to a model in which the regions on the secondary star where stellar activity occurs seem to be preferentially on the side facing the white dwarf and contain loop-type structures surrounding the secondary. A similar white dwarf–facing activity concentration and a similar multipiked Hα line has been observed in V471 Tau (Young et al. 1991). The Hα emission-line satellites have been stable for over 2 yr in AM Her, and VV Pup showed a similar Hα emission-line structure during one of its recent low states (Mason et al. 2006).

4.3. Additional Observational Study

Stellar activity, as evidenced by emission lines such as H and Ca, is usually an optical bandpass specific proxy. Even very active stars (see Fig. 12) show little obvious evidence for chromospheric activity in their near-IR and IR spectra. The reason that activity emission is so weak in the near-IR and IR bands is both a contrast effect and one of line formation. The activity-induced emission lines in an active binary are often “filled in” by the emission from the bright photospheric continuum. In addition, the typical spectral lines present in the IR region that one might expect to be in emission and associated with stellar activity (e.g., J- to K-band H i Paschen series and Ca lines) form too low in the stellar atmosphere to be greatly modulated or affected by an active chromosphere. In CVs, the contrast effect just mentioned can be provided by the high-state accretion flux or accretion disk light, hiding not only the secondary but any possible activity-induced lines. In addition, CV emission lines are generally very broad due to the high velocities in the disk or stream, again able to hide weaker, narrow lines caused by activity. Polars in low states offer the lack of additional (accretion) flux contribution allowing secondary star activity indicators to be observed in the optical. However, formation of the higher energy IR lines deeper in the stellar atmosphere still renders the 1–3 μm region a poor choice in the search for chromospheric activity. Indeed, near-IR spectroscopy of EF Eri obtained after the optical emission lines appeared (Johnson et al. 2005) shows no sign of hydrogen or any other emission lines. Also, ST LMi was observed at 2.2 μm during a low state, and no emission lines were seen, although Balmer emission was present (Howell et al. 2000). Thus, searches for stellar activity in CV secondaries are probably limited to low-state observations in the optical, and as such, are mainly restricted to polars.

Low-state observations, such as those presented herein, are generally difficult to gather, as they require optical spectroscopy, often as target-of-opportunity observations, with fairly large telescopes, as low-state polars tend to be faint. Phase-resolved spectroscopy is required, as the origin and cause of the spectral emission (or absorption; see Mason et al. 2006) features observed must be firmly determined. A single spectrum or even a single epoch of observations can easily confuse activity with irradiation. Polars are probably the easiest targets for this purpose, as they show their high/low state directly, while the VY Scl stars might be considered prime targets to go after, as we know little about their low states or their secondary stars.

We have added new direct spectroscopic evidence into the mix of understanding high/low states of polars and if and how these mass-transfer changes are related to stellar activity. The simple idea of the turn-on of stellar activity directly starting and stopping mass transfer (i.e., high and low states) seems ruled out, as activity turned on in EF Eri yet remained low for another 1.5 yr, while stellar activity seems ever present in the secondary during low states of the polars AM Her and VV Pup. Just as we were
finishing this paper, EF Eri reentered a high state, reaching \( V = 15.6 \) on 2006 March 4 (R. Stubbings 2006, private communication). Data obtained up to the time of this rebrightening (see Figs. 8, 9, and 11) reveal no obvious change in the radial velocity, emission distribution on the secondary, or the EW of H\( \alpha \) directly before the high state started. Our monitoring programs show EF Eri to be currently providing all its usual high-state properties observed in the past, even after its 9 yr hiatus.

We want to make a special mention here of the undaunted observational effort of Rod Stubbings, who, for over 9 yr, observed EF Eri and provided us with nothing—nothing to report that is—on EF Eri being visible, until a few weeks prior to concluding work on this paper when his e-mail subject line “EF Eri brightened!!!” caught the attention of astronomers over the world. Thanks Rod! We want to acknowledge Sandy Leggett and Tom Geballe for obtaining the \( K \)-band images of EF Eri, and UKIRT for its continued service observing program. Margaret Hanson kindly obtained the spectra of RS CVn for us. Frank Hall and Mark Giampapa have generously contributed their time to converse on and provide a great resource for information related to stellar activity on solar-like stars. We thank the referee for providing a number of useful comments. We are grateful for the support of Dean of Arts and Sciences J. Staros, Provost R. McGrath, and Vice President for Research G. Habich, all of Stony Brook University, for providing partial support that enabled Stony Brook’s participation in the SMARTS consortium. We thank the SMARTS service observers J. Espinoza, D. Gonzalez, and A. Pasten for taking the data, and for their dedication to the SMARTS effort. We thank C. Bailyn, the driving force behind the SMARTS consortium, for his leadership. This research was funded in part by NSF grant AST 03-07454 to Stony Brook University. Some of the observations used herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration, made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Maunakea has always had within the indigenous Hawaiian community. We are most fortunate to have the opportunity to conduct observations from this mountain. Part of this work was performed (M. E. H and R. H. B) under the auspices of the US Department of Energy, National Nuclear Security Administration by the University of California, Lawrence Livermore National Laboratory, under contract W-7405-Eng-48. We wish to thank the IAU for permission to reproduce Figure 11. Finally, S. B. H. wishes to thank ESO headquarters in Chile for their support, and my host, E. Mason, for her coffee and cooking, which provided a wonderful working environment and allowed the completion of this paper.

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ONSET OF CHROMOSPHERIC ACTIVITY IN EF ERI

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