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WHY ARE THE SECONDARY STARS IN POLARS SO NORMAL?

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ABSTRACT

We have used NIRSPEC on Keck II to obtain *K*-band spectroscopy of several magnetic cataclysmic variables. These data reveal that the secondary stars in these binary systems have spectra that are consistent with normal, late-type dwarfs in both their atomic and molecular line strengths, as well as in the slopes of their continua. This result is in stark contrast to the infrared spectra of their nonmagnetic cousins, nearly all of which show peculiar abundances, especially of CNO species and their isotopes. It appears that the evolutionary path taken by the secondary stars in magnetic systems differs from that for the nonmagnetic systems. We discuss the implications of this result.

Subject headings: binaries: close — stars: magnetic fields

1. INTRODUCTION

Cataclysmic variables (CVs) are short-period binary systems consisting of a white dwarf primary that is accreting material via Roche lobe overflow from a low-mass, late-type secondary star. CVs can be divided into two main classes: magnetic and nonmagnetic. In magnetic systems, the primary white dwarf has a strong magnetic field ($0.5\ \mathrm{MG} \leq B \leq 240\ \mathrm{MG}$). In "polars," the magnetic field of the white dwarf is strong enough to capture the accretion stream close to the secondary star. In "intermediate polars" (IPs), the magnetic field of the white dwarf is believed to be weaker ($B \leq 8$ MG) and is insufficient to completely prevent the formation of an accretion disk. IPs therefore exhibit behavior that can be unique or common to both magnetic and nonmagnetic classes.

The commonly proposed evolutionary history for CVs has been assumed to be similar for both the magnetic and nonmagnetic systems (King et al. 1994; Kolb 1995) and has three main phases. First, the orbital separation of the wide binary of the pre-CV is rapidly shrunk in a common envelope phase where the secondary star orbits inside the red giant photosphere of the white dwarf progenitor. The second phase is a very long epoch where gravitational radiation or a magnetically constrained wind from the secondary star extracts angular momentum from the binary (magnetic braking), resulting in the eventual contact of the photosphere of the secondary star with its Roche lobe. The final phase begins once the secondary star contacts its Roche lobe, mass transfer to the white dwarf is initiated, and all of the phenomena associated with CVs are observed.

Based on the current paradigm (see Howell et al. 2001 and references therein), it can be argued that the majority of secondary stars in CVs should show little signs of evolution at the time of contact: the duration of the CV formation process is a small fraction of a low-mass star's main-sequence lifetime. In addition, after contact, the secondary star begins to *lose mass*, extending its lifetime, and preventing it from ever forming an He-burning core (Howell 2001). Recent results, however, challenge this idea. Infrared spectroscopy of two dozen CVs by Harrison et al. (2004, 2005) and UV spectroscopy (Gänsicke et al. 2003 and references therein) find evidence for peculiar abundance ratios in the secondary stars of nonmagnetic CVs. The dominant anomalies are deficits of carbon and enhancements of nitrogen. In addition, several CVs show evidence for enhanced levels of ^{13}CO in their *K*-band spectra. Taken together, these results suggest that CNO-processed material has found its way into the photospheres of CV secondary stars. Either the accretion of material during the common envelope phase and/or from classical novae eruptions is much more efficient than expected, or the secondary stars in nonmagnetic CV systems started out with much larger masses (to allow CNO burning) than current population synthesis theories predict. If magnetic systems followed the same evolutionary path prior to the contact phase, then they too should have secondary stars with similar abundance anomalies. In the following we present new infrared *K*-band spectroscopy for five polars: VV Pup, ST LMi, AR UMa, MR Ser, and SDSS J1553+5516.

2. OBSERVATIONS

Infrared spectroscopy for the program objects was obtained using NIRSPEC[1] on Keck II in photometric conditions on 2005 February 17. A journal of our observations is presented in Table 1. We used NIRSPEC in low-resolution mode with a 0".38 slit. The grating tilt was set so as to cover the wavelength region $2.04\ \mu\mathrm{m} \leq \lambda \leq 2.46\ \mu\mathrm{m}$, with a dispersion of 4.27 Å pixel^{-1}. We employed the two-nod script, and we used 4 minute exposure times for all of the program CVs. To correct for telluric absorption, we observed bright A0 V stars located close to the program objects so as to minimize their relative differences in air mass. These data were reduced using the IDL routine REDSPEC, specially

[1] For more on NIRSPEC go to http://www2.keck.hawaii.edu/inst/nirspec/nirspec.html.

TABLE 1
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Object	P_{orb} (hr)	Number of Exposures	Start (UT)	Stop (UT)	Spectral Type
VV Pup	1.674	22	08:23	10:04	M7
AR UMa	1.932	6	10:23	10:50	M5.5
ST LMi	1.898	6	10:56	11:23	M6
SDSS J1553	4.39	12	13:27	14:24	M4.5
MR Ser	1.891	12	15:06	16:00	M8

developed for NIRSPEC.[2] In the *K* band, the spectra of A0 V stars are nearly featureless, except for the prominent H I Brγ feature at 2.16 μm. The REDSPEC package does not attempt to correct for this feature but can interpolate across such lines to reduce their impact on division into the program star spectrum. Note that there is a weak telluric feature located very close to the Brγ line, and thus the H I line profiles in spectra produced by the division of a "patched" A star spectrum are slightly compromised.

In Figure 1 we present the final, medianed spectra of VV Pup, ST LMi, AR UMa, and SDSS J1553+5516. The NIRSPEC spectrum of MR Ser is shown in Figure 2, where it is compared to a 2003 May spectrum obtained using SPEX on the Infrared Telescope Facility (IRTF). As seen in Table 1, the time spent on ST LMi and AR UMa was relatively short, ≲10% of an orbital period, and thus smearing of the secondary star features due to orbital motion is not significant. This is not the case for VV Pup, SDSS J1553+5516, and MR Ser. For MR Ser and VV Pup we have used published ephemerides by Schwope et al. (1993) and Walker (1965) to correct for the radial velocity motion of their secondary stars. A radial velocity analysis of the VV Pup data set presented here (S. B. Howell et al. 2005, in preparation) confirms the phasing from Walker (1965). No such ephemerides exist for SDSS J1553+5516, and thus the orbital motion of its secondary star cannot be accounted for. Fortunately, its spectrum does not show signs of significant smearing. The spectra in Figure 1 have been smoothed to a resolution of 5.1 Å pixel^{-1} to allow us to directly compare them to spectra of late-type dwarfs obtained using SPEX on the IRTF (from Harrison et al. 2005). It is important to note that the REDSPEC package flux calibrates the spectra using a blackbody spectrum while the SPEXTOOL package (Vacca et al. 2003) used to produce the late-type dwarf spectra from SPEX data employs a model A star atmosphere. Any subtle differences in the slopes of the continuua between the program objects presented here and the late-type templates observed with SPEX could in fact be due to the slightly different flux cali-

[2] Details about the REDSPEC package can be found at http://www2.keck.hawaii.edu/inst/nirspec/redspec/index.html.

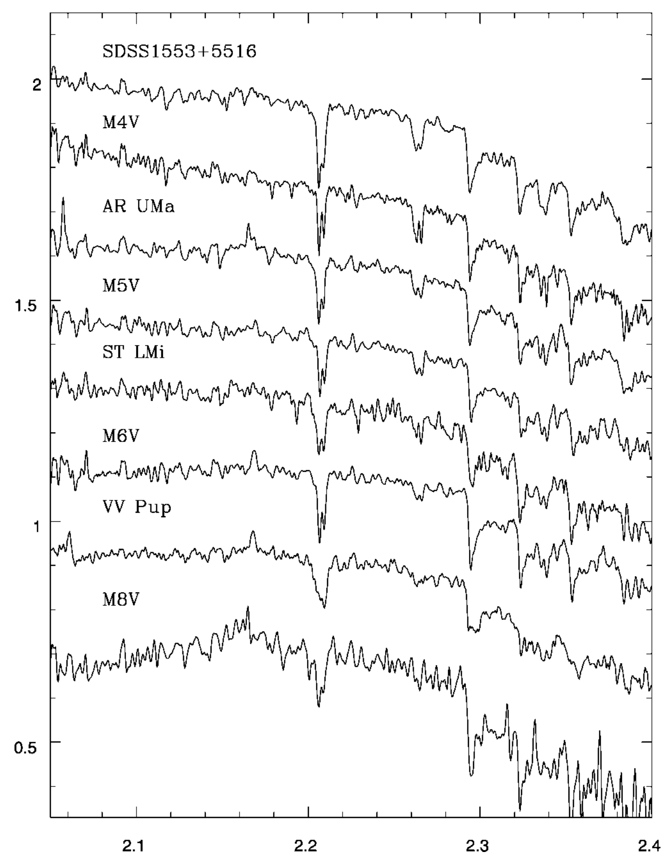

Fig. 1.—Program object spectra compared to the spectra of some late-type dwarfs. To provide a slightly more realistic match to the program object spectra, the data for the M5 V, M6 V, and M8 V spectra have been rotationally broadened to 150 km s^{-1}, while the M4 V spectrum has been broadened to 110 km s^{-1}.

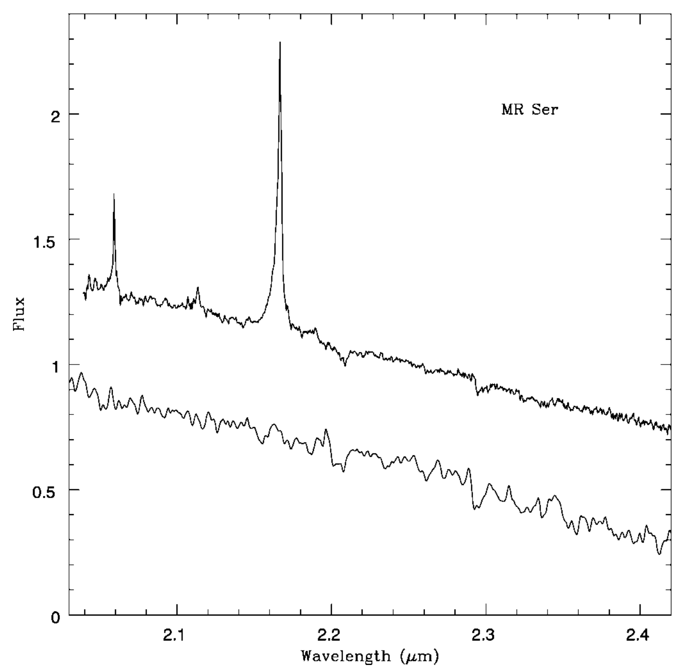

Fig. 2.—NIRSPEC data for MR Ser (*top*), compared with the IRTF+SPEX spectrum obtained in 2003 May. Emission lines from He I at 2.06 and 2.11 μm and H I Brγ at 2.16 μm are present in the NIRSPEC data, but not in the SPEX data. Clearly, MR Ser was in a "high state" in 2005 February. The NIRSPEC data have been Gaussian smoothed to a resolution of 5.1 Å pixel^{-1}, while the SPEX data have been smoothed to a resolution of 40 Å pixel^{-1}.

bration procedures used by the two packages, and not due to any intrinsic differences.

3. RESULTS

Close examination of the spectra shown in Figure 1 reveals no significant abundance anomalies (for identifications of the stronger spectral features found in late-type dwarfs see Harrison et al. 2005). The atomic absorption lines and CO absorption features appear to have strengths that are consistent with those expected for late-type dwarfs. We have derived spectral types for each of the secondary stars and list them in Table 1. The spectral features in VV Pup are somewhat broader and/or weaker than in the other program objects, suggesting a large rotational velocity or improper phasing. VV Pup was also the faintest of the five polars, and thus its spectrum is somewhat noisier. Even with this, it is clear that the Na I doublet (near 2.20 μm) in VV Pup has a strength relative to the CO features (at 2.294 μm, and redward) that is consistent with it being a normal, very late M-type dwarf. As demonstrated by the weakness of their emission lines, all of the polars (except MR Ser) were in low states, a time when the accretion rate from the secondary star drops to a very low value and the activity level of the system declines. As seen in Figure 2, the emission lines from He I and H I in MR Ser were prominent, suggesting that it was in an active state, although no visual estimates of the system brightness exist to confirm this conclusion. Due to this activity level, the spectrum of the secondary star in MR Ser is considerably diluted compared to that observed during a lower level of activity. During the low state, analysis of the IR spectrum of MR Ser obtained with SPEX on the IRTF led to a classification of M8 V. Thus, the secondary stars of these five polars, plus that of the prototype system, AM Her (Harrison et al. 2005), appear to be relatively normal late-type dwarfs.

That the secondary stars of polars show no evidence for peculiar abundance patterns is in stark contrast to our results for nonmagnetic systems (Harrison et al. 2004, 2005). In those efforts, only a single system (IP Peg) out of 20 CVs had a secondary star with normal CO absorption features. *This suggests that the evolutionary histories of magnetic and nonmagnetic systems are different.*

Since all known CV secondary stars have masses below 1.3 $M_{\odot}$, generating peculiar abundances via the CNO cycle in CV secondary stars cannot occur after contact (Howell 2001). Thus, any observed abundance anomalies either (1) are the result of normal stellar evolution during the pre-CV phase, (2) are due to material of peculiar composition being accreted during the common envelope phase, or (3) come from the accretion of classical nova ejecta once the mass transfer phase ensues (see Marks & Sarna 1998). Both magnetic (e.g., V1500 Cyg, Stockman et al. 1988; CP Pup, Diaz & Steiner 1991; V2214 Oph, Baptista et al. 1993; V2487 Oph, Hernanz & Sala 2002; BT Mon, White et al. 1996; GQ Mus, Diaz & Steiner 1994) and nonmagnetic systems have been observed as classical novae. As shown in calculations by Livio et al. (1988), the field strengths found in polars (and expected in IPs) are insufficient to inhibit, or dramatically alter, classical nova outbursts. Thus, the accretion of nova ejecta as an explanation for unusual abundance patterns in CV secondary stars appears to be eliminated. It is critical, however, to show that one or more of the classical novae listed above are true polars and are not simply IPs like the prototype magnetic classical nova DQ Her.

Kolb (1995), King et al. (1994), and Liebert et al. (2005) all conclude that the presence of a highly magnetic "white dwarf" primary cannot strongly affect the common envelope phase of evolution unless the secondary star orbits close to the magnetospheric radius of the magnetic core. If true, we are left to conclude (under the standard CV evolutionary paradigm) that the abundance anomalies we detect in nonmagnetic systems must be due to evolutionary effects in the secondary stars themselves. This implies that the secondary stars of nonmagnetic systems must start life with a mass sufficient to initiate the CNO cycle ($M \geq 1.3\ M_{\odot}$) so as to enrich some layers within their atmospheres. The current, low-mass secondary star is then the stripped remains of this more massive object.

If peculiar CNO abundances in nonmagnetic CVs result from normal stellar evolution, then the secondary stars in polars must have entered and exited the precontact phases with masses similar to what is currently observed. Given the observed preference of polars to have shorter periods than nonmagnetic systems (see King et al. 1994 and references therein), it is relevant to ask whether all CVs below the famous period gap are simply the product of pre-CV binaries with initially low-mass secondary stars. The UV study by Gänsicke et al. (2003) shows that at least one, normal, nonmagnetic system below the period gap, BZ UMa, shows a large N V/C IV emission line ratio. It is vital to attempt to obtain data on more CV systems below the period gap to investigate whether this is true for all short-period nonmagnetic systems.

A recent far-ultraviolet survey of 11 polars by Araujo-Betancor et al. (2005) finds normal N V/C IV emission line ratios for several systems, indicating that the material being transferred to the white dwarf in those polars is not of unusual composition, adding further weight to our results. We note, however, that the *asynchronous*, long-period polar, BY Cam, has extreme N V/C IV line ratios (Mouchet et al. 2003), providing at least one, albeit peculiar, counterexample. The strong correspondence between the N V/C IV emission line ratios in the UV and the strength of the secondary star's CO features in the IR is remarkable, and it appears that one can be used as a proxy for the other.

We conclude that the evolutionary history of most polars appears to differ from that of the majority of nonmagnetic CVs. While the exact origin for this difference could be the initial masses of their secondary stars, it is hard to understand why low-mass binaries preferentially go on to produce magnetic white dwarf primaries. A related conundrum is the apparent lack of "prepolars" (Schmidt et al. 2005; Wellhouse et al. 2005 and references therein), binary systems containing magnetic white dwarf primaries and main-sequence secondary stars that are not in contact with their Roche lobes. Does the magnetism of the white dwarf primary accelerate the precontact evolution to the point that nearly all polars are born in their currently observed states? Schmidt et al. (2005) suggest that the small family of "low accretion rate polars" (LARPs; Schwope et al. 2002), including SDSS J1553+5516, are in fact the prepolars. However, EF Eri is currently behaving in a fashion that is *similar* to this group of LARPs, a condition attained only 7 yr after an observed high state (Harrison et al. 2004). Given the ability of EF Eri to get stuck in such a prolonged low state, it is probably too early to conclude that the recently discovered LARPs never have high states.

Our results for magnetic systems have shed new light on nonmagnetic systems. It now seems that the most likely path for the extreme levels of carbon depletion found in nonmagnetic systems is the precontact evolution of the secondary star. The secondary stars in most nonmagnetic CVs must have started out life with much higher masses than is observed now, in direct conflict with population synthesis theories.

Given this scenario, it is interesting to postulate whether Algols might be the progenitors of CVs. Algols are plentiful, both components in most systems appear to have had initial masses high enough to ignite the CNO cycle during their lifetimes, and many Algols have orbital periods (∼1 day) that fall in the range to make suitable pre-CV candidates. In addition, the stellar components in numerous Algol systems show peculiar abundances of CNO elements, including enhanced levels of nitrogen and deficits of carbon (Cugier & Hardorp 1988; Cugier 1989; Parthasarathy et al. 1983; Tomkin & Lambert 1989). Two particularly relevant Algols, which already have total system masses similar to those of the longest period CVs, are TT Hya and S Cnc. Both TT Hya and S Cnc have B9.5 V primaries and cool late-type giant/subgiant secondary stars with exceptionally small masses of 0.4 and 0.2 $M_{\odot}$, respectively (Olson & Etzel 1993; Etzel 1988). The existence of a "flip-flop," where the primary star and secondary star switch roles, was long ago (Paczyński 1971) proposed to explain the presence of low-mass, evolved secondary stars in Algols with high-mass primaries. It might be time to explore the possibility that a subset of Algols are the progenitors of nonmagnetic CVs, where the peculiar secondary stars in both are the remnant "cores" of the same, once more massive stars.

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