Irradiation of CV secondaries

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Abstract. In many cases, the red secondary star in a cataclysmic variable (CV) system contributes a significant amount to the total near-IR and IR flux. Over the past decade, several CV secondaries have been observed; however, the interpretation of these observations is complicated by the fact that one hemisphere of the secondary is subjected to the intense radiation fields of the primary, accretion disk, and boundary layer. Using our general purpose atmosphere code (PHOENIX), we have modeled the effects of the impinging radiation from a hot white dwarf on the atmosphere of a CV secondary. We will present preliminary results for an average CV system.

1. Introduction

Over the past decade, several authors have observed the red secondary star in CV systems at near-IR and IR wavelengths (e.g. Z Cha, Wade & Horne (1988); GD 245, Schmidt, Smith, & Harvey (1995); GD 448, Marsh & Duck 1996). At these wavelengths, the red dwarf becomes a major contributor to the overall flux from the CV despite the presence of a much hotter white dwarf and accretion disk. These observations are extremely important for determining the properties of the secondary, which in turn have strong implications for the evolution of post/pre common envelope systems. In the following contribution, we focus on the heating of the secondary by radiation from the primary and modeling the effects on the atmospheric structure and the resulting spectrum.

Model construction

For this preliminary study, we have chosen a typical CV system consisting of a 20000 K white dwarf located near a 3000 K M dwarf. Both white dwarf and M dwarf have been modeled as plane parallel slabs in local thermodynamic equilibrium (LTE). The WD model is described in Barman et al. (2000) and the details of the non-irradiated M dwarf model are found in Hauschildt, Allard, & Baron (1999).

The usual boundary conditions for an isolated star are that the inward directed flux at the surface should be zero ($I^b_{\infty}(\tau = 0, \mu) = 0$, where $-1 \leq \mu =$
\[ \cos(\theta) \leq 0 \text{ and } \tau \text{ is the optical} \] and that the diffusion approximation holds at the bottom of the atmosphere. For a close binary, the situation is clearly different. At the surface of the secondary, the boundary condition on \( I^{\uparrow}_\nu \) is determined by the incident flux \( F^{inc}_\nu \) given by:

\[
2\pi \int_{-1}^{0} I^{\uparrow}_\nu(\mu) \mu d\mu = F^{inc}_\nu(\tau = 0)
\]

where

\[
F^{inc}_\nu(\tau = 0) = \left( \frac{R^*}{a} \right)^2 F^*_\nu.
\]

In the equations above, \( I^{\uparrow}_\nu(\mu) \) refers to the inward directed intensities along direction \( \mu \), \( R^* \) is the radius of the primary, \( a \) is the surface to surface primary-secondary separation, and \( F^*_\nu \) is the monochromatic flux from the primary. For \( F^*_\nu \), we use a synthetic spectrum taken from a previous PHOENIX calculation. For the models presented below, we have made the simplifying assumption that the impinging radiation field is isotropic, meaning that \( I^{\uparrow}_\nu(\mu) \) at the surface is the same for all \( \mu \) (i.e., \( I^{\uparrow}_\nu(\mu) = I^{\uparrow}_{\nu,0} \)). This assumption overestimates the amount of flux received by the secondary and, therefore, our models represent upper limits to the effects of irradiation. All models are subject to an energy conservation constraint such that the total flux (convective plus radiative) is constant:

\[
F_{\text{tot}} = F_{\text{rad}} + F_{\text{conv}} = 2\pi \int_{-1}^{1} \left( I^{\downarrow}_\nu + I^{\uparrow}_\nu \right) \mu d\mu = \sigma T_{\text{eff}}^4.
\]

Energy conservation requires that all of the incident radiation from the primary be re-radiated outward by the secondary in the form of reflected flux and as a contribution to the thermal flux.

2. Results

The impact of the incident radiation on the M dwarf atmosphere is made most apparent by the changes to the temperature structure. In the top left panel of Fig. 1, we compare the non-irradiated M dwarf structure to the structures of two irradiated models: one with an orbital separation of 5 \( R_\odot \) and a second with an orbital separation of only 1 \( R_\odot \). When the M dwarf is located 5 \( R_\odot \) from the white dwarf, little change occurs in the majority of the atmosphere except for a large temperature inversion in the very optically thin regions (\( \tau_{1,2} < 10^{-4} \)) of the atmosphere. However, at 1 \( R_\odot \), a significant temperature increase occurs throughout the atmosphere, even at large optical depths. Also, convection has been slightly suppressed as the radiative-convective boundary has moved closer to \( \tau_{1,2} = 1.0 \).

The large temperature inversion (at 1 \( R_\odot \)) has strong effects on the M dwarf spectrum. The irradiated M dwarf shows a dramatic increase in the infrared pseudo continuum and a forest of narrow emission lines appear from the ultraviolet through the optical (see lower left panel of Fig. 1). Also shown in Fig. 1 is
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Figure 1. The atmospheric structures (top left) and corresponding spectra (bottom left) for a (3000 K) M dwarf irradiated by a (20 000 K) white dwarf at orbital separations of 5.0 and 1.0 \( R_\odot \). For comparison, the non-irradiated model (grey) is also shown. Note that \( \tau_{1,2} \) refers to the optical depth in the continuum measured at 1.2 microns. In the right panel, the spectra for the white dwarf, irradiated M dwarf and the combined flux (black line) are shown. The resolution of the spectra have been reduced to 5 Å to facilitate comparison.

the primary and secondary spectra as well as the combined flux. Near 7000 Å, the slope of the continuum changes sign as the M dwarf begins to dominate the near infrared flux. Many of the emission lines predicted in our model are seen in the observations of GD 245 by Schmidt et al. (1995).

Many authors have used the variation with orbital phase of the Na I doublet near 8200 Å (in conjunction with other atomic and molecular features) to obtain orbital data for CV systems and to probe the conditions in the M dwarf photosphere. In Fig. 2, we show the effects of irradiation on the concentration of neutral Na in our M dwarf model. There is a significant reduction of neutral Na throughout the atmosphere which is, roughly, inversely proportional to the temperature rise seen in Fig. 1. Also, the change in Na I concentration can be seen in the reduced equivalent width of the Na doublet compared to the non-irradiated model’s spectrum (see Fig. 2 inlay).

3. Conclusions

In this preliminary study, we have demonstrated that dramatic changes occur in the atmospheres of CV secondaries due to the incident flux from the primary. Our results indicate that many of the emission lines and equivalent width variations observed in CV systems are, at least, partially a result of irradiation. The next step is to improve our models by relaxing the assumption of LTE since the
Figure 2. Concentration of Na I in our irradiated (solid line) M dwarf with an orbital separation of 1 R⊙ and non-irradiated (dash-dotted line) model (see text for details). Also shown, the change in a Na I doublet due to irradiation.

presence of an external radiation source should inherently be a non-LTE problem. We also plan to generate large grids of irradiated M dwarfs to construct more complete models of the heated secondary surface which will be important for interpreting observations with high time resolution.

References