Eclipse Mapping the Chromosphere of the M4Ve Binary
CM Dra: First Results

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Abstract:
We present a preliminary analysis of HST FOS rapid readout spectra (1 s resolution) of Mg III during two secondary eclipses in the dM4e binary CM Dra. Several flares were observed in both the Mg II line and in the nearby continuum, which we use to estimate the contribution of flares to atmospheric heating. After removing the flares, we study the shape of the eclipse in Mg II. The Mg II lightcurve during the first eclipse shows subtle differences between ingress and egress, implying a non-uniform chromosphere. Larger differences between eclipses suggest that short-term evolution may be significant. We discuss the prospects for inverting the lightcurve to produce maps of Mg II variations across the stellar surface. Analysis of a FUV spectrum of CM Dra reveals C II, Si IV and C IV emission for the first time.

1. Introduction

CM Draconis (=GL 630.1A), a double M4Ve system, is currently the smallest and least massive eclipsing binary known ($R_A = 0.252R_\odot$, $R_B = 0.235R_\odot$, $M_A$ and $M_B$ both < 0.24$M_\odot$; Lacy 1977, Metcalfe et al. 1996). The space motion of CM Dra (suggesting it is a Pop II object) together with the existence of a white dwarf with common proper motion (GL 630.1B), implies the system is quite old. Despite their age, however, both stars are magnetically active due to their tidally-enforced rapid rotation in a short period orbit ($P_{\text{rot}} = P_{\text{orb}} \approx 1.268$ d). Spots, flares (Lacy 1977), and significant chromospheric (Doyle 1987) and coronal emission (Dempsey et al. 1997) have all been detected.

The eclipses of the system offer an unusual opportunity to study the spatial structure of the stars’ atmospheres by using the occulting star as a mask. The slightly “off-center” eclipses present in CM Dra not only provide latitude information from ingress/egress differences, but partly resolve the north-south ambiguity as well. In this preliminary analysis, we study timeseries of the chromospheric Mg II line flux taken with HST using simple models.

2. Observations and Analysis

Spectra of the Mg II region were obtained at 1 s resolution with the HST FOS using the G270H grating. Continuous observations through two entire eclipses (feasible, since CM Dra is in the continuous viewing zone [CVZ] of HST) were planned to help discriminate flares from real structure. Unfortunately, problems
with scheduling led to the second observation being cut short (the star is only just inside the CVZ, and thus rarely available as a CVZ target). We also obtained a short wavelength spectrum with the G130H grating outside the eclipse.

The data were analyzed with standard HST software and special purpose code written in IDL. Figure 1 shows the average Mg II flux during the first eclipse.

![Average Spectrum: CM Dra Eclipse 1](image)

Figure 1. The average flux at earth during the first CM Dra eclipse observed. The positions of the Mg II and “continuum” (a region relatively free of strong emission lines) integration windows are indicated.

Mg II at 2800Å is strong, and many weaker lines (mostly Fe II) are also visible. The Mg II lines rest on a background composed of a variable UV continuum plus scattered light. We measured this background was by integrating counts in relatively line-free window near Mg II (Fig. 1), and subtracting a scaled version of this from the integrated Mg II counts. Figure 2 shows the average short wavelength spectrum taken outside of eclipse; C II (1335Å), Si IV (1394, 1403Å) and C IV (1550Å) are clearly detected here (for the first time) at surface fluxes of $f = 1.0, 0.7,$ and $2.3 \times 10^{-14}$ ergs cm$^{-2}$ s$^{-1}$ at earth, respectively. Converting to surface flux ($\times 4.2 \times 10^{18}$; based on radii from Lacy 1977 and a distance from Chabrier & Baraffe 1995) yields $F = 4.2, 3.3,$ and $9.8 \times 10^4$ ergs cm$^{-2}$ s$^{-1}$, making CM Dra slightly less active than the dM4e+dM5e system EQ Peg (cf. Rutten et al. 1989). The average Mg II outside the first eclipse, $F_{\text{MgII}} = 4.2 \times 10^5$ ergs cm$^{-2}$ s$^{-1}$, is identical with an IUE measurement (Doyle 1987).

3. Modelling and Discussion

For studying and modeling the eclipses, we have binned the data into 5 s intervals to improve the S/N. The latest phase information was kindly provided by L.R. Doyle (1997) from his photometric program. A plot of the (background corrected) Mg II and the continuum count rates for both eclipses against phase (Figure 3) already shows several interesting features:
Figure 2. The average flux at earth in the far UV just outside of eclipse. C II, Si IV, and C IV are clearly detected here; C III (1175Å), C I (1277-80Å), and S I (1486Å) may also be detected.

Figure 3. Counts per 5 s in a continuum window (see Fig. 1) and Mg II as a function of phase for eclipse 1 (solid) and eclipse 2 (dot-dashed). The 1 σ noise per point is indicated.

1. There is a significant difference in flux level in the eclipse ingress for the two eclipses not attributable to either a very long flare in the eclipse 1 (since ingress and egress flux levels are almost identical), or an instrumental effect (e.g., target miscentering).

2. The eclipse shapes agree fairly well (excluding flares) close to ϕ = 0.500.

3. There are numerous weak flares in both the continuum and Mg II.
In this initial study, we constructed simple eclipse models on a 100×100 grid (Fig. 4), using the radii and orbital parameters (other than phase) taken from Lacy (1977). We assumed the eclipsing star (CM Dra B) had a non-variable $<F_{\text{MgII}}>$ equal to the typical value on CM Dra A’s surface, and set limb darkening of both stars to zero. A uniform model for CM Dra A fits eclipse 1 (E1) quite well (Fig. 5, red curve), with the model eclipse only slightly too deep just prior

![Figure 4](image1.png)

**Figure 4.** The non-uniform stellar models in eclipses 1 (left) and 2 (right). Light gray indicates a Mg II surface flux 20% of the white areas; the arrow indicates the motion of the eclipsing star.

![Figure 5](image2.png)

**Figure 5.** Eclipse 1 plus model results (top) for CM Dra A with uniform (thin red/dark gray) or off-center inactive polar cap model with polar regions at 20% of the peak Mg II (green/light gray; stellar model in Fig. 4-left); the ±1σ data RMS is indicated (dashed). At bottom is the continuum band flux with ±1σ errorbars; throughout timesteps where the continuum appears enhanced by flares are marked by dotted lines. The difference (data-model) for the non-uniform model is shown with the data RMS (middle). With the flares are masked out, $\chi^2_{\nu} = 1.2$ and 1.5 for the non-uniform and uniform models, respectively.
to $\phi = 0.50$. If we use continuum excursions to identify flares and mask these from the Mg II data, the reduced $\chi^2$ for the uniform model is $\chi^2_{\nu} = 1.5$. Some improvement can be obtained for a model with a slightly off-center polar region of reduced emission (20% of the initial value); $\chi^2_{\nu}$ drops to 1.2 (Figs. 4-left & 5, green curve). This model is by no means unique, but is likely indicative of a family of models yielding acceptable fits. Fundamentally though, the star at this epoch seems fairly uniform, given the reasonable fit with the uniform model.

Eclipse 2 (E2) requires a significant drop in overall flux, and very significant spatial inhomogeneities, as indicated by the changes in slope in the Mg II lightcurve (Fig. 3). We started with our best model for E1 and modified it until a reasonable fit was achieved (Figs. 4-right and 6, green curve). The large difference in eclipses on ingress, and later agreement near eclipse minimum requires (given our assumptions) a significant drop in Mg II flux for the eclipsed region of CM Dra A prior to $\phi = 0.5$. Our final model (Fig. 4-right) is once again not unique; for example, a drop in Mg II flux on some part of CM Dra B could account for some of the difference between eclipses (though it could not explain the eclipse shape differences. For this model $\chi^2_{\nu} = 5.6$ compared to $\chi^2_{\nu} = 1.6$ for the non-uniform model.

![Figure 6. Eclipse 2 plus model results (top) for CM Dra A with uniform (thin red/dark gray) or modified eclipse 1 model (green/light gray; stellar model in Fig. 4-right). As in Fig. 5, the continuum with marked flares (dotted) and the data-model residuals are shown (bottom and middle curves). Here the uniform model clearly fails, yielding $\chi^2_{\nu} = 5.6$ versus $\chi^2_{\nu} = 1.6$ for the non-uniform model.]
$F_{\text{MgII}}$ defined in this manner is quite small ($\sim 1\%$ of the total), the flares are numerous, affecting 32\% of our timesteps in E2 and 23\% in E1.

Our original plan to eclipse map the Mg II distribution on CM Dra A, perhaps performing an inversion on the Mg II timeseries using a maximum entropy-type approach (e.g., Collier-Cameron 1997), has thus run up against two interesting problems:

- The CM Dra chromospheres can change significantly on timescales of one orbit (1.268 days)
- Weak flares are sufficiently numerous to complicate the analysis.

It seems likely that either several eclipses of data are needed (to better extract flares and identify possible “quiet” times when the star is not changing as rapidly), or that star simply changes so rapidly that detailed maps of the outer atmosphere are not meaningful for long time periods.

Acknowledgments. This work was based on observations obtained with the NASA Hubble Space Telescope, which is operated by AURA under NASA contract NAS5–26555. SS and JB were supported by a NASA HST grant for program GO–5515. We thank J. Valenti for helpful comments.

References

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