Semi-empiric Radiative Transfer Modeling of FUSE Stellar Spectra

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Abstract. We present an overview of radiative transfer modeling efforts to interpret spectra of a variety of stellar objects observed with FUSE. Detailed radiative transfer modeling of high ion emission line profiles of C\textsc{iii} and O\textsc{vi} observed in the far-UV spectrum, provides a powerful means to probe the thermal and dynamic properties of high-temperature plasmas in the atmospheres of stars. We model asymmetric emission lines of C\textsc{iii} \( \lambda 977 \) (and Mg\textsc{ii} \( h & k \)) observed in spectra of luminous cool stars such as \( \alpha \text{Aqr} \), to infer the wind- and microturbulence velocity structures of the upper chromosphere. Semi-empiric radiative transfer models that include transition region temperature conditions, are further developed based on detailed fits to O\textsc{vi} resonance emission lines in the supergiant \( \alpha \text{Aqr} \), the classical Cepheid variable \( \beta \text{Dor} \), and to self-absorbed O\textsc{vi} emission lines in the cataclysmic variable SW\textsc{uma}.

We observe that the C\textsc{iii} resonance line profile of \( \alpha \text{Aqr} \) assumes a remarkable asymmetric shape, reminiscent of P Cygni type profiles observed in hot luminous supergiants. The model calculations indicate outflow velocities above \( \sim 140 \text{ km s}^{-1} \) at kinetic temperatures of 65 kK and higher. Based on detailed model fits to the narrow red-shifted and self-absorbed O\textsc{vi} emission lines of SW\textsc{uma} we compute that the gas- and electron density exceed the density conditions of the upper solar transition region by about three orders of magnitude. We propose that the large gas density of \( \rho \sim 1.4 \times 10^{-11} \text{ gr cm}^{-3} \) favors a region of warm dense plasma of 100 kK \( \leq T_{\text{gas}} \leq 300 \text{ kK} \) that collapses onto the white dwarf with a mass accretion rate of \( 1-2 \times 10^{15} \text{ g s}^{-1} \) above or between the accretion disk. We discuss how detailed semi-empiric fits to emission lines observed with the high spectral resolution of FUSE can provide reliable constraints on the mass loss or mass accretion rates in these objects. The complete text of this conference presentation is available at cfa-www.harvard.edu/~alobel/conference.html

1. FUSE Observations and Detailed Radiative Transfer Modeling

We present a comparative study of transition region (TR) wind dynamics in \( \alpha \text{Aqr} \) (G2 Ib), SW\textsc{uma} (CV), \( \beta \text{Dor} \) (F-G Ia-Iab) and the Sun, to develop semi-empiric radiative transfer models of the thermal structure of the stellar chromosphere and TR, and to determine the velocity and electron density structures. FUSE spectra of the hybrid supergiant \( \alpha \text{Aqr} \) have been observed for Science Team Program P218 (Dupree et al. 2005). The classical \( \delta \)-Cepheid variable \( \beta \text{Dor} \) was observed in Aug. and Oct. 2003 for GI-D107 (PI A. Lobel), while the
dwarf nova SW UMa was observed in Nov. 2001 for GI-B074. The left-hand panel of Fig. 1 shows non-LTE radiative transfer fits to C III λ977 through a semi-empiric model of the chromosphere and lower TR of α Aqr. The outward decrease of ρ (panels right) produces a scattering core in the computed emission profile (Lobel & Dupree 2000; 2001), which assumes an asymmetric shape due to opacity in a fast accelerating wind. Best multi-level atom model fits are obtained for $V_{\text{wind}} > 140$ km s$^{-1}$ in the lower TR ($T \simeq 65$ kK), which strongly scatters the blue emission line wing. The model signals a supersonic optically thick warm wind in the outer atmosphere of this hybrid supergiant (Lobel & Dupree 2002).

The left-hand panels of Fig. 2 show O VI lines in the cataclysmic variable SW UMa. The lines are remarkably far red-shifted with respect to heliocentric rest. We suggest that the double-peaked narrow profiles result from self-absorbed emission line formation in an infalling region near the white dwarf that

Figure 1. Radiative transfer best fit (solid line) to C III λ977 in α Aqr.

Figure 2. Best fit (long-dash dotted line) to O VI λ1032 & λ1037 in SW UMa.
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Figure 3. Best fit to solar O \textsc{vi} (upper left panel) emission compared to $\beta$ Dor.

is sufficiently optically thick at $T_{\text{gas}}$ between 100 kK and 300 kK (panels right). The depth of the O \textsc{vi} $\lambda$1032 central absorption line core can only be computed with electron densities $N_e$ at least 1100 times larger compared to the solar TR values. The downflow velocity ($V_{\text{wind}}$) in the model is computed from the conservation of total mass in spherical geometry with $\dot{M} = 4 \pi \rho(r) V_{\text{wind}}(r) (r+R_{\text{WD}})^2$, using a mass accretion rate $\dot{M}$ of $1 \times 10^{15}$ g s$^{-1}$, and $R_{\text{WD}}=0.01 R_\odot$. This $\dot{M}$-value provides the best fit to the wavelength position of the central self-absorption core where $V_{\text{wind}}=+70$ to $+65$ km s$^{-1}$ in the O \textsc{vi} lines formation region.

The upper left-hand panel of Fig. 3 compares the O \textsc{vi} lines we compute with an atmospheric model of the average quiet Sun with SOHO-SUMER observations (solid dots). The lines form over a rather small region of $\sim$10 model layers with $100 \text{kK} \leq T_{\text{gas}} \leq 300 \text{kK}$, or $\sim$200 km into the solar TR above the upper chromosphere (panels right). A best fit to the FWHM and equivalent width of the lines is obtained with projected microturbulence velocities ($V_{\text{turb}}$) increasing from at least $\sim$30 km s$^{-1}$ to $\sim$39 km s$^{-1}$ over this thermal range (Warren et al. 1997). A best fit to the core position of the O \textsc{vi} $\lambda$1032 line is computed with a mean downflow velocity of $+5$ km s$^{-1}$. Preliminary atmosphere models for $\beta$ Dor (lower left panel) require $V_{\text{turb}}$ exceeding 40 km s$^{-1}$ in the O \textsc{vi} lines formation region to match the large line widths we also observe in $\alpha$ Aqr.

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References

Dupree, A. K., Lobel, A., Young, P. R., Ake, T. B., Linsky, J. L., & Redfield S., 2005, ApJ, submitted
Lobel, A., & Dupree, A. K. 2000, ApJ, 545, 454
Lobel, A., & Dupree, A. K. 2001, ApJ, 558, 815
Lobel, A., & Dupree, A. K. 2002, FUSE Science and Data Workshop, March 2002, Abstract Poster Talk, p. 60, full poster text at cfa-www.harvard.edu/~alobel/fuseposter.pdf
Warren, H. P., Mariska, T. J., Wilhelm, K., & Lemaire, P. 1997, ApJ, 484, L91