SYNTHETIC SPECTRA FOR ACCRETION DISCS: THE UV ABSORPTION SPECTRUM

R. A. WADE
Pennsylvania State University,
Department of Astronomy & Astrophysics,
525 Davey Lab, University Park PA, 16802, USA

1. Spectrum synthesis on a large grid of disc models

With my collaborators (Ivan Hubeny, NASA/Goddard Space Flight Center; Marcos Diaz, Catherine Grant, and Darren Williams, all of Penn State), I am computing the structure of discs and their corresponding UV spectra for a large grid of choices of the white dwarf mass $M_{\rm wd}$ and the mass transfer rate $\dot{M}$. In our approach, we divide the problem into a number of parts, each corresponding to a particular FORTRAN-implemented computer program. Program **TLUSDISK** computes the vertical structure for individual rings in the disc (T, ρ, $n_{\rm e}$, τ *versus* z). The rings are treated independently, as plane-parallel entities without irradiation, obeying the standard expression for $T_{\rm eff}$ as a function of $M_{\rm wd}$, $R_{\rm wd}$, and $\dot{M}$. With this vertical structure, program **SYNSPEC** computes the detailed local (rest frame) spectrum for each ring. Both *specific intensities* and angle-averaged *fluxes* can be computed. Program **DISKSYN** is used to combine the spectra of individual rings to obtain the integrated or whole-disc spectrum, taking into account Doppler shifts (dependent on the chosen disc inclination) and limb darkening. Finally, program **ROTINS** is used to smooth the spectrum to an appropriate instrumental resolution. Intermediate results, e.g., from **TLUSDISK** or **SYNSPEC**, are stored for repeated use.

Specific modeling choices have been made. These include the use of the Reynolds number to specify the disc viscosity, a vertical dissipation law parameterized by ζ as in equation (6) of Long et al. (1994), the assumption of LTE, and the neglect of irradiation. Winds and wind albedos have also been neglected. Steady-state disc structure has been assumed, and boundary layer emission has been neglected. Simple opacities have been used in computing the vertical structure, including H and He line and continuum opacities and scattering by free particles. Full line lists of many elements

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have been used in computing the spectra from the models. Further details of the modeling can be found in Long et al. (1994) and references therein.

For the models discussed here, a Reynolds number $\Re_e = 5000$ has been chosen. The α viscosity parameter varies inversely with $\Re_e$. The ζ parameter has been chosen to be 2/3. Reasonable changes in these values are explored below.

The computer codes are flexible enough to handle certain non-LTE computations, to incorporate prescribed irradiation or wind albedos, and additional opacity sources can be included. The steady-state assumption can be dropped when appropriate. A long-term goal is to explore the effect of the choices on the computed spectra. Nevertheless, the present grid of models and spectra can usefully be taken as benchmarks and as initial guides to the interpretation of observations.

We have computed models over most of a rectangular grid in $(M_{\rm wd}, \dot{M})$ space, with $\log \dot{M}$ (in $\mathrm{M_\odot\,yr^{-1}}$) varying in steps of 0.50 from −10.5 to −8.50 and $M_{\rm wd}$ taking values of 0.350, 0.550, 0.800, 1.030, and $1.210\,\mathrm{M_\odot}$. The corresponding values of $R_{\rm wd}$ are 11.424, 9.049, 6.985, 5.177, and 3.783 ($\times 10^8$ cm). Except for the largest value of $M_{\rm wd}$, this makes a grid whose diagonals correspond to the same run of $T_{\rm eff}$ with dimensionless radius $x = R/R_{\rm wd}$. Ring radii increase roughly logarithmically from $x = 1.05$ until $T_{\rm eff}(x)$ falls below roughly 10 000 K. The maximum disc temperature occurs at $x = 1.36$ and varies from 16 500 K to 69 500 K in the present models. Fluxes and specific intensities (at several emergent angles) have been computed on the wavelength interval 1150...1900 Å for the rings and full discs of these models. Over this interval, the restriction to $T_{\rm eff} > 10\,000$ K is not harmful.

2. Results

Only a few points can be highlighted here. A fuller discussion will be published in the serial literature.

2.1. OPTICAL DEPTH

In this class of models (with $T_{\rm eff} > 10\,000$ K) the Rosseland mean optical depth τ, measured vertically from the disc midplane, is least at the inner edge of the disc. At $x = 1.05$, it is larger for low $M_{\rm wd}$ and for high $\dot{M}$. Values of $\tau < 4$ occur at $x = 1.05$ in some models with $\dot{M} \leq 10^{-10}\,\mathrm{M_\odot\,yr^{-1}}$. For a broad range of temperatures and densities, the continuous absorption coefficient declines substantially with decreasing wavelength toward the H I Lyman edge, suggesting that transparency effects will likely show up first at the inner edge and at far UV wavelengths.

2.2. HEIGHT OF DISC PHOTOSPHERE

The height of the photosphere $z(\tau = 1)$ measured from the midplane will be governed by the temperature scale height at the midplane, which in turn varies with $T_{\rm eff}$ and the midplane optical depth. Since τ depends on the surface density, one expects that increasing the Reynolds number will increase the scale height at fixed R for a given ($M_{\rm wd}$, $\dot{M}$) model. This is verified in the detailed computations, with $z(\tau = 1) \propto \Re_{\rm e}^{1/4}$ for intermediate models. The standard result that $z(\tau = 1)$ increases more rapidly than R (e.g. Pringle 1981) is recovered also. For $M_{\rm wd} = 1.15\,{\rm M}_\odot$ and $\dot{M} = 4.5\,10^{-9}\,{\rm M}_\odot\,{\rm yr}^{-1}$(not on the regular grid), the outer disc thickness corresponds to an opening angle of about 3° for $\Re_{\rm e} = 5000$. The vertical component of the gravitational acceleration falls off somewhat more slowly than $g \propto R^{-2}$.

For disc rings that are quite optically thick, the choice of the viscosity distribution parameter, ζ, has very little effect on $z(\tau = 1)$ for $0.05 < \zeta < 1$. Varying ζ from 0.05 to 1 varies the midplane temperature by less than 10% in optically thick rings.

2.3. LIMB DARKENING AND LINE BLENDING

Figure 1 of Wade, Hubeny & Polidan (1994) illustrates several features of the UV spectrum for a particular disc with $M_{\rm wd} = 0.8\ {\rm M}_\odot$ and $\dot{M} = 10^{-10}\ {\rm M}_\odot\ {\rm yr}^{-1}$. These include the complex blending of many absorption lines and the very strong limb darkening in the UV. The line blends change dramatically with disc inclination in details of strength and pattern because of the Doppler effect. This will be of diagnostic value for UV spectra of high resolution and S/N ratio.

Limb darkening (LD) will occur in any photosphere with a non-inverted temperature gradient. LD is qualitatively similar in (optically thick) discs and stars, but is more important for discs than for stars because the entire disc is viewed at (nearly) the same emergent angle, so the effect occurs *without dilution*. LD is stronger in the UV (describable with linear LD coefficients close to unity) as a consequence of the wavelength dependence of the source function. It is also stronger for cooler photospheres as a consequence of the temperature dependence of the source function at fixed wavelength. This directly affects the interpretation of 'brightness temperature' maps and of UV–R 'colour–magnitude' diagrams that have been made for eclipsing cataclysmic variables. The locus of disc surface elements in a colour–magnitude plane may be distorted because of the λ–dependence of LD. The shape of the $T_{\rm br} - \log R$ plot (made at a specific wavelength) may be distorted because of the T–dependence of LD. Statements regarding the distance of a CV or whether it is in steady state need to take LD into account. The contribution by Diaz, Wade & Hubeny (1996) in the present volume discusses disc LD further.

The finite opening angle of a disc means that the front and back parts of a disc are viewed at different angles, as noted by Robinson et al. (1995). In this case *differential* LD will need to be taken into account in eclipse-mapping studies. It is important to note that the amount of disc flaring is not a free parameter, to be determined independently of the $T_{\rm br}$–R relation; rather, they must be determined in a mutually consistent way, since they are both manifestations of the underlying disc structure.

2.4. DISC SPECTRA AND WHITE DWARF SPECTRA

As discussed in somewhat more detail in Wade, Hubeny & Polidan (1994), discs at low mass transfer rates have UV spectra that are similar to solar abundance white dwarfs. The kinematic line smearing in discs mimics the pressure broadening of lines in a white dwarf photosphere. With typical *IUE* spectra and the usual uncertainty in the distances of CVs, this results in a major interpretive problem. The ambiguity can be broken given sufficient wavelength coverage; sufficient wavelength resolution and S/N; or independent information about the distance or disc inclination of the CV to remove the excess degrees of freedom in fitting the spectrum.

3. Conclusions

LTE spectra of model rings differ little from stellar atmosphere spectra computed in the same way with the same opacities. This is because radiative transfer and hydrostatic equilibrium in stars and discs are basically similar. Intuition about stellar atmospheres pays off if carefully applied to discs. In spite of their approximations and omissions at the present stage, disc models are sufficiently far advanced that one need not resort to blackbody approximations or angle-averaged fluxes when interpreting observations of cataclysmic variable discs.

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