RADIATIVE TRANSFER IN THE DYNAMIC ATMOSPHERES OF LONG PERIOD VARIABLE STARS

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Abstract   An iterative procedure is presented for determining the thermal structure and dynamics of Mira–type stellar atmospheres, where the non–LTE radiative transfer code PANDORA is used in conjunction with the Bowen hydrodynamics code of Iowa State University. We report on preliminary results for an atmospheric model of a pulsating AGB star of $1\ M_\odot, 240\ R_\odot, T_{eff} = 3000\ K$, and a period of 320 days. At the present time, H, H^-, Mg I, and Mg II radiative transfer calculations have been completed and synthetic spectra are shown for H–α. The radiative transfer calculations demonstrate that cooling in the innermost shock of the original Bowen model is underestimated due to the omission of various hydrogen transitions. These initial results suggest that the main shock of the Bowen models are too hot and/or too deep.

INTRODUCTION

Mira variables are asymptotic giant branch (AGB) stars that show evidence for pulsations in their spectra and light curves. Hydrodynamic models for Mira variables have been generated by Bowen (1988). Due to the intrinsic computational difficulty of handling radiative transfer in a dynamic medium, radiative cooling in these *first generation* models is approximated in a simiplified manner (cf., Bowen 1988). These approximations essentially ignore important low temperature coolants like the Mg II h and k and Ca II H and K lines and energy sources and sinks like H–α, H and H^- free–free, thermal conductivity, and the Lyman and Paschen continua.

The radiative transfer code PANDORA has been used to compute emergent spectra for a variety of different stellar environments including the Sun (Vernazza, Avrett, and Loeser 1981), the M–type supergiant α Orionis (Hartmann and Avrett 1984), and the N–type carbon star TX Psc (Luttermoser *et al.* 1989). PANDORA solves the equations of radiative transfer and statistical equilibrium in either plane parallel or spherical geometry in a self–consistent manner. Macroscopic velocity fields can be included in the calculation of the line profiles, source functions, and rate equations.

COMPUTATIONAL PROCEDURE

Hydrodynamic calculations of pulsating stars generally require many time steps over a given cycle and a large number spatial zones ($\sim$200 time steps and $\sim$500 zones in the Bowen code). Such a large parameter space prevents the inclusion of detailed radiative transfer calculations due to the large amount of CPU time required to converge a model. The modelling introduced here represents *second generation* dynamic models (Bowen's original models being the *first generation*) of long period variables in that the radiative transfer is handled in *snapshots* throughout a given pulsation cycle. Such an approximation assumes that the time derivative in the net rate equation is zero. *The velocity gradient term however is not set to zero as would be the case in a pure statistical equilibrium calculation.* To reduce computer time, a *snapshot* of the temperature–density–velocity stratification is taken at intervals of 1/8th of the cycle in the dynamic Bowen models. For these eight *snapshots*, we select 55 depths out of 520 zones with the following procedure: (1) the odd numbered zones between zone 1 and 30 (representing the unshocked photosphere) are selected; (2) temperature minima and maxima and additional zones near the innermost shock are selected between zones 31 and 250; (3) the remaining depths (maximum of 55) are selected uniform intervals from zone 251 to 520.

Once the PANDORA input is constructed, the following radiative transfer calculations are made in sequence with output from the preceeding used as input for the next stage. (1) A 3–level hydrogen model atom is used in a static, plane–parallel medium. H–α is treated explicitly and Ly–α and Ly–β are assumed to be in detailed balance. Balmer and Paschen photo–ionization rates are approximated with an input radiation temperature. (2) A 3–level hydrogen atom is used in a static, spherically symmetric medium. All rates are handled in detail. Upon convergence of these models, the macroscopic velocity fields are then included in the calculations. (3) Mg I (7–levels) and Mg II (6–levels) calculations are made first assuming a static, plane–parallel medium and then a dynamic, spherically symmetric medium.

Upon convergence of the eight PANDORA models (one for each of eight phases), calculated electron densities and net cooling rates are mapped back into the Bowen hydrodynamics code and a new dynamic model is calculated. Once again, eight *snapshots* are obtained from the new model and the process repeated. This iterative procedure continues until a consistent model is achieved.

INITIAL RESULTS

Temperature, density, and velocity profiles for the first–generation 3000 K model can be found in Bowen (1988). Figure 1 displays the H–α line profile calculated with the assumptions of the second item listed above (static case) for phases 0.00, 0.25, 0.50, and 0.75. The variation of these H–α profiles mimic the variations seen in Mira-type variables. However these profiles, which are scaled to the average angular diameter of o Ceti, are far too broad as compared with observations of any LPV star. This is an opacity effect and not a velocity effect

since these profiles are calculated in a static medium and suggests the innermost shock is too hot and/or too deep throughout the cycle.

The radiative transfer calculations demonstrate that the approximations used by Bowen (1988) for radiative cooling underestimate total hydrogen cooling in the main, innermost shock since it ignores all hydrogen transitions except Ly-α. At phase 0.00, the dominant hydrogen coolants in the main shock (T$\sim$12,000 K, z$\sim$$-2.5x10^7$ km, negative sign indicates height above the continuum formation depth at 5000Å) are Paschen and Balmer ionization, H ff, and H-α respectively. At phase 0.25, the dominant coolants are H$^-$ ff, Paschen and Balmer ionization, Ly-β, and H$^-$ ff in the main shock (T$\sim$12,000 K, z$\sim$$-1.0x10^8$ km). The main shock at phase 0.50 (T$\sim$8000 K, z$\sim$$-2.0x10^8$ km) has Ly-α, H-α, H$^-$ ff and bf, Paschen and Balmer ionization, and H ff respectively. Finally phase 0.75 has Paschen and Balmer ionization, H ff, H$^-$ ff and bf, H-α, and Ly-α as the dominant coolants in the innermost shock (T$\sim$10,000 K, z$\sim$$-1.8x10^7$ km). Thermal conduction is also included in these calculations but was found to be unimportant.

ACKNOWLEDGEMENTS

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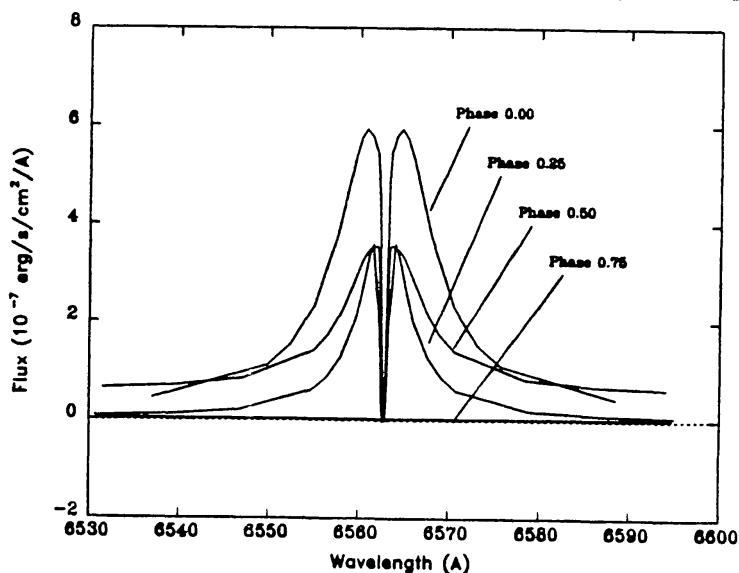Vernazza, J.E., Avrett, E.H., and Loeser, R. 1981, *Ap. J. Suppl.* **45**, 635.

Figure 1: H-α profiles at various phases of the *first generation* models in a spherically symmetric, static medium.