HYDRODYNAMICS AND MULTI-LEVEL NON-LTE RADIATIVE TRANSFER IN PULSATING ATMOSPHERES: CEPHEIDS

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The atmospheres of classical Cepheids cannot be represented adequately by a sequence of hydrostatic equilibrium atmospheric models (see Sasselov and Lester 1990 and references therein). Observational evidence for shocks is also available at least since Kraft (1956). Both the disequilibrium and the non-linear phenomena affect the emergent spectra and spectral line profiles of the Cepheids. In the lower amplitude variables the effects may be subtle, yet still lead to significant systematic discrepancies.

We have developed the code HERMES for time-dependent treatment of hydrodynamics and non-LTE radiative transfer in the *atmospheres* of classical Cepheids with periods shorter than 12 days. Our approach is applicable to stars in which the formed shock waves do not dominate the energy balance of the atmosphere. Consecutive detailed calculations are performed for several multi-level model atoms, including H, Ca II, Mg II, He I and II. We use a 1-D explicit conservative upwind monotonic second-order (in time and space) Godunov-type Lagrangian hydrodynamic scheme. Being a characteristics based scheme it allows natural handling of boundary conditions. The scheme is stable and without artificial dissipation, a crucial necessity for physically meaningful radiative transfer solutions (see Roe 1990, Sasselov and Raga 1991 for more details).

We present time-dependent models of Cepheid atmospheres, built in a semi-empirical way and with forms of the driving piston of the pulsation taken from interior envelope computations. At present we have studied the ways in which the non-linear phenomena in a pulsating atmosphere affect different spectral lines, and the effect on measured observables (*e.g.*, velocities, temperatures, etc.). A few brief notes can be made at this time. The major effect to the velocities measured from Doppler shifts of spectral lines is due to shock waves in a Cepheid atmosphere. These are, however, of no big concern because of their transient nature (less than 10% of the cycle length) and usually obvious impact on the line profile (line doubling, emission). Much more subtle, but by no means small, are the effects due to velocity gradients in a Cepheid atmosphere. These gradients stretch the contribution function of a photospheric line over a large interval of velocities, even for narrow depth-constrained transitions. The resulting profile is asymmetric, but smooth, and not mutilated. The asymmetry due to a velocity

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gradient couples with the asymmetry due to the geometric projection effect, and produces a composite line profile, which is rarely strongly asymmetric, yet has a "wrong" Doppler shift. This nonlinear phenomenon, unlike shocks, is not transient, and may affect the photosphere for a quarter and more of the cycle length (longer for longer-period Cepheids). And, unlike geometric projection effects, it cannot be treated in a prescribed way – every Cepheid is affected according to its specific atmospheric structure and dynamics (*i.e.* the phases at which velocity gradient asymmetry and projection asymmetry couple differ). Finally, its effect on the velocity measured from the spectral lines is the same as that from the projection effect, for Cepheids of about 10 days period, *i.e.* a 20% effect. Both the frequency and the magnitude of the velocity gradient increase with period (luminosity) and amplitude.

The propagation of even weak shocks in a Cepheid atmosphere is related to the development of strong velocity gradients. The lack of shocks does not exclude velocity gradients. Most classical Cepheids exhibit strong symptoms of transient shock waves, therefore it should be expected that velocity gradients affect the profiles of their spectral lines. Semi-empirical consistent modelling of hydrodynamics and non-LTE radiative transfer of Cepheids is already feasible and should be used to improve the accuracy of the basic parameters of these stars as inferred from observations of their atmosphere (radii and distances, modes, etc.).

References

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