

The Centre-of-Mass Velocity of a Radially Pulsating Star: Insights from NLTE Models

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Abstract. The problem of deriving the centre-of-mass velocity of a radially pulsating star is reexamined. New observations of line asymmetry and Non-LTE radiation hydrodynamics point to a systematic effect of about 1 km s^{-1} in Cepheids.

1. Introduction

Accurate measurements (better than 1 km s^{-1}) of the centre-of-mass velocity of a pulsating star, commonly referred to as γ -velocity, are needed both for kinematic studies (e.g., Pont et al. 1994) and for determining radii and distances using the Baade-Wesselink (BW) method (Gautschy 1987).

The standard method to measure the γ -velocity from an observed radial velocity curve requires the integral

$$\int (v_{\text{rad}} - \gamma) d\phi = 0,$$

when extended over a whole cycle. Thus path conservation is a basic assumption in the BW method (Gautschy 1987). From this also follows the constancy with phase of the projection factor, $p \equiv V_{\text{pulsation}}/V_{\text{radial}}$. The p -factor is used in a BW solution to convert from observed radial velocities to pulsation velocities.

Karp (1975) studied the systematics in Cepheid γ -velocities from hydrodynamic models with *gray* atmospheres. He found no significant systematic effect above 0.4 km s^{-1} . We reexamine the problem with more realistic models and in view of new observational evidence.

2. The new observational evidence and non-LTE models

Discrepant asymmetries of the photospheric spectral lines in Cepheids and RR Lyraes indicate that path conservation *may not* be valid. Naively one expects the asymmetry of spectral lines to be a simple function of radial velocity over the cycle. What is observed in Cepheids is very different – large asymmetry during contraction, much reduced asymmetry during expansion (Butler 1993; Albrow & Cottrell 1994; Sabbey et al. 1995).

The discrepant line asymmetries are reproduced by the radiation hydrodynamics NLTE models of Cepheids (Sasselov & Raga 1992), as caused by the varying depth of line formation and coupled opacity changes (see Sabbey et al.

1995 for details). It is crucial that the atmosphere is *not gray* and that the NLTE radiative transfer is coupled to the hydrodynamics. Otherwise none of these spectral line effects are treated properly, as noted by Karp (1975) himself and shown further by Albrow (1994) with line-blanketed LTE synthetic spectra on a separately computed first-order hydrodynamic model after Wood (1974).

3. Practical considerations

While the systematic effects discussed here have been suspected to exist for more than three decades now, there has been no direct empirical evidence to help determine their magnitude. Therefore current use of radial velocity curves involves an implicit assumption of zero average line asymmetry over a cycle. Sabbey et al. (1995) showed that this assumption is not good at the 5–10% level of accuracy.

As a solution, we suggest that the line asymmetry curves be used *in conjunction with* the radial velocity curves of Cepheids. First, the radial velocity curve should be measured from Doppler shifts of selected photospheric lines (see Butler 1993 for lists) with a knowledge of the spectral line profiles. For example, some methods measure Doppler shifts from the minimum of an absorption line profile, others take a weighted mean, etc. Second, the asymmetry curve should be obtained for the same list of photospheric lines. If the asymmetry curve is not symmetric, i.e., the average is not zero, corrections to both the γ -velocity and p -factor must be made. In the case of deriving a phase-dependent p -factor, this can be accomplished directly from the observations. One needs to quantify the asymmetry curve in terms of Doppler shift (in wavelength or velocity), depending on which method was used above to measure the radial velocities, e.g., see Fig. 3 in Sabbey et al. (1995). In the case of the γ -velocity, the deviation of the asymmetry curve from a zero-average (in units of Doppler shift) would provide most of the needed correction. Part of this correction depends on the details of line formation and is thus model dependent. Its model dependence can be reduced substantially by observing the asymmetry curves of a large number of photospheric lines with different excitation potentials.

References

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