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# Rotation and the Cepheid Mass Discrepancy

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**Abstract.** We recently showed that rotation significantly affects most observable Cepheid quantities, and that rotation, in combination with the evolutionary status of the star, can resolve the long-standing Cepheid mass discrepancy problem. We therefore provide a brief overview of our results regarding the problem of Cepheid masses. We also briefly mention the impact of rotation on the Cepheid period-luminosity(-color) relation, which is crucial for determining extragalactic distances, and thus for calibrating the Hubble constant.

**Keywords.** stars: evolution, stars: rotation, supergiants, Cepheids, distance scale

## 1. Introduction

Classical Cepheids are evolved intermediate-mass stars observed during brief phases of stellar evolution that render them highly precise standard candles. They are furthermore excellent laboratories of stellar structure and evolution thanks to their variability and location in the Hertzsprung-Russell diagram. Despite the adjectives *classical* and *standard*, Cepheids are all but sufficiently well understood. A key symptom of this is the 45-year-old Cepheid mass discrepancy problem (Christy 1968; Stobie 1969a,b,c) that has been estimated until recently to be in the range of $10-20\%$ (Bono *et al.* 2006) and has motivated much research into convective core overshooting (e.g. Prada Moroni *et al.* 2012) and enhanced mass-loss (Neilson & Lester 2008).

## 2. Rotation to the Rescue

While convective core overshooting is successful in increasing core size and thereby increasing luminosity at fixed mass, it cannot fully explain the mass discrepancy, since high values ($\geqslant 20\%$ of pressure scale height) of convective core overshooting also suppress the appearance of blue loops at the low-mass end, cf. Anderson *et al.* (2014, Fig. 1). This is a problem, since the majority of Cepheids are understood to reside on blue loops and have short periods, i.e., they originate from relatively low ($\sim 5\,M_\odot$) mass B-stars.

We recently presented the first detailed investigation of the effect of rotation on populations of classical Cepheids (Anderson *et al.* 2014) based on the latest Geneva stellar evolution models (Ekström *et al.* 2012; Georgy *et al.* 2013) that incorporate a homogeneous treatment of rotation over a large range of masses. We found that rotation, together with evolutionary status (i.e., identification of the instability strip (IS) crossing) can resolve the mass discrepancy, and mass-luminosity relations (MLRs) of models for typical initial rotation rates agree better with observed Cepheid masses than models without rotation, see Fig. 1. Furthermore, rotation does not suppress the appearance of

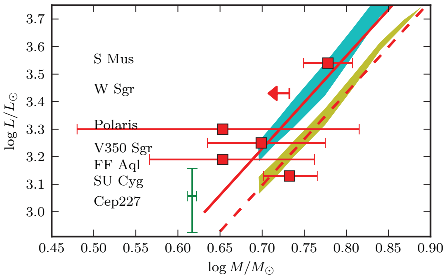


**Figure 1.** Mass luminosity relations of rotating models (higher $L$) better reproduce observed Cepheid masses than non-rotating ones, see Anderson *et al.* (2014) for more details and references.

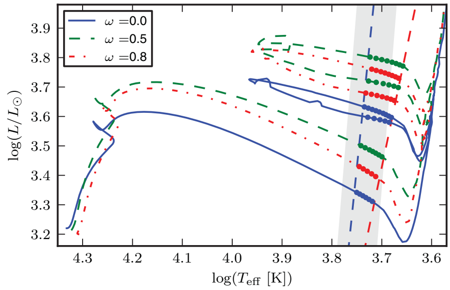


**Figure 2.** Evolutionary tracks for a $7\,M_\odot$ model with Solar metallicity and different initial rotation rates quantified by $\omega = \Omega/\Omega_{\rm crit}$. The effect of rotation during the main sequence carries through to the later evolutionary stages.

blue loops (cf. Fig. 2) and is thus in better agreement with observations than models invoking high overshooting values.

## 3. Implications

An important consequence of rotation is that no unique MLR applies to all stars. The farther a star evolves along the main sequence, the larger this difference tends to become. The difference in main sequence turn off luminosity between models of different rotation rates carries over into the more advanced evolutionary stages. For Cepheids, luminosity also tends to increase between the 2$^{\rm nd}$ and 3$^{\rm rd}$ IS crossings, adding further complexity. To estimate a Cepheid's mass given the luminosity, its evolutionary status must therefore be taken into account. Measured rates of period change provide empirical measurements of the IS crossings, and are furthermore sensitive to initial rotation.

Finally, we point out that rotation can lead to intrinsic scatter in the period-luminosity relation (PLR) and the period-luminosity-color-relation (PLCR). The PLCR follows from inserting an MLR into the pulsation equation ($P \propto 1/\sqrt{\bar\rho}$, Ritter 1879). As there is no unique MLR (cf. above), there cannot be a unique PLCR. This finding has potentially important implications for the accuracy of Cepheid distances and thus for the distance scale. Further investigation in this direction is in progress.

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