THE PHYSICS BEHIND THE NON-LINEARITY OF THE CEPHEID PERIOD-LUMINOSITY RELATION

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ABSTRACT

Recent observational work has suggested that the Cepheid period-luminosity (PL) relation in the LMC is non-linear. This is because the period-colour (PC) relation in the LMC is also non-linear leading to a non-linear LMC PL relation. We present a possible theoretical explanation for the break in the PC relation. Our explanation relies on the interaction of the hydrogen ionization front with the Cepheid photosphere and the way this interaction changes with phase of pulsation and metallicity to produce the observed changes in the Cepheid PC and PL relation.

Key words: Cepheid; Stellar Structure and Pulsation; Distance Scale.

1. INTRODUCTION

The Cepheid period-luminosity (PL) relation is a major component in the distance scale ladder. The current most commonly used calibrating PL relation is based on the Large Magellanic Cloud (LMC) Cepheids (as in Freedman et al. 2001). This is always regarded as a linear function of $\log(P)$ within the range of $\log(P)$ ~0.3 to $\log(P)$ ~2.0, where P is pulsation period in days. However, the non-linearity of the LMC PL relation has been proposed in Tammann et al. (2002), Kanbur & Ngeow (2004) and Sandage et al. (2004), i.e., the LMC PL relation can be broken into two PL relations, one for short- ($\log(P)$ <1.0) and one for long-period Cepheids. Further, Kanbur & Ngeow (2004) found that the break seen in the LMC PL relation is statistically significant with the F-test.

The reason for the break in LMC PL relation is because the LMC period-colour (PC)[1] relation is also broken (see Figure 1). On the other hand, the Galactic PC relation is fully consistent with a single regression line, i.e., there is no break in the Galactic PC relation (Tammann et al. 2003; Kanbur & Ngeow 2004). Recall that both of the PL and PC relations follow the PLC relation for Cepheid variables (see Madore & Freedman 1991 for the basic physics of PLC relation). Hence, understanding the physics behind the break in the LMC PC relation helps in the understanding of the break as seen in the PL relation. The study of the broken PC relation is not only important in distance scale studies (the effects of broken PL and PC relation should be taken into consideration when deriving the Cepheid distances), but also important in the study of stellar structure, evolution and pulsation that need to account for this newly discovered phenomenon.

[1]The colour is referred to the $<V> - <I>$, where $<X>$ is the (intensity) mean magnitude.

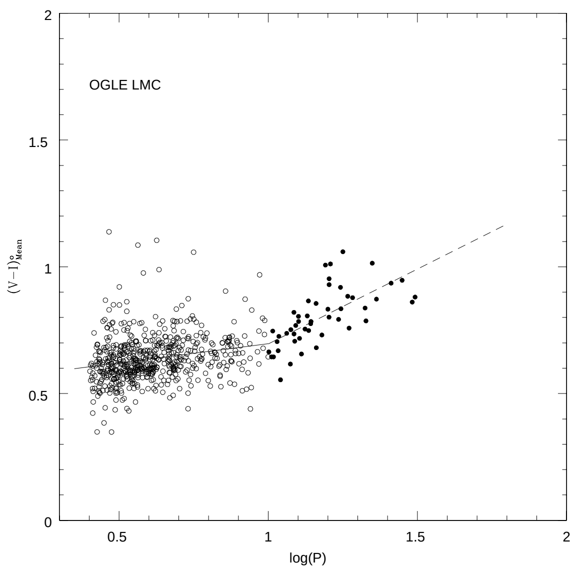

Figure 1. The LMC period-colour (PC) relation. The open and solid circles are for short ($\log(P)$ <1.0) and long period Cepheids, respectively. The lines are the fitted PC relations to these Cepheids.

2. THEORY & MODELS

The current working hypothesis to explain the break of the LMC PC relations is first presented in Kanbur & Ngeow (2004) and in Kanbur et al. (2004), and more details will be presented in a future paper. Here we briefly outline the hypothesis and the pulsation models needed to account for the broken LMC PC relation. The proposed hypothesis is:

The interaction of the hydrogen ionization front (HIF) with the photosphere (at optical depth of $2/3$) at certain phases of pulsation (for some period range) is responsible for the break in the PC relation.

It is well-known that the partial hydrogen ionization zone exists in the envelope of a pulsating star. As the star pulsates, this zone moves in and out in the mass distribution envelope. Therefore, it is possible that the HIF will interact with the photosphere at certain phases of pulsation. For example, this interaction produces a flat PC relation at maximum light (Simon et al. 1993). At other phases, since the HIF does not interact with the photosphere, the temperature of the star (or the colour) follows the underlying PC relation. Figure 2 illustrates this interaction in the temperature profile when the photosphere is located at the base of HIF and no interaction if the photosphere is far away from the HIF. This interaction has successfully explained the flat PC relation at maximum light for the long period ($\log(P)$ >0.8) Galactic Cepheids (Simon et al. 1993; Kanbur et al. 2004).

We use the Florida pulsation codes, which include a 1-D turbulent convection recipe (Yecko et al. 1998), to construct the Galactic and the LMC models, in order to investigate if the physics behind the broken PC relation is due to the HIF-photosphere interaction. The pulsation codes take the mass (M), luminosity (L), effective temperature ($T_{\rm eff}$) and chemical composition (X, Z) as input parameters. The chemical compositions are appropriately chosen to represent the Galactic and LMC Cepheids. The mass and luminosity are connected with the ML relations calculated from evolutionary models. Here we choose the ML relations from Chiosi (1989) and Bono et al. (2000). The $T_{\rm eff}$ are chosen to ensure the models oscillate in the fundamental mode and are located inside the Cepheid instability strip. The pulsation periods for the models are obtained from the linear non-adiabatic analysis.

After the models are constructed from the codes, we plot out the temperature profile in terms of the internal mass distribution ($\log[1 - M_r/M]$, see Figure 2). The locations of the HIF and photosphere are then identified in the temperature profile. To quantify the HIF–photosphere interaction, we calculate the 'distance' in $\log(1 - M_r/M)$ between the HIF and the photosphere. This 'distance' is denoted as Δ as illustrated in Figure 2. Hence, small Δ means there is HIF–photosphere interaction, and vice versa. Since the behaviour of the PC relation at mean light is the average of all phases, hence it is important to study the PC relation at different phases (e.g., at maximum and minimum light). Therefore, Δ is calculated at maximum and minimum light from the models and plotted out as a function of pulsation period.

3. PRELIMINARY RESULTS & CONCLUSION

In Figure 3, we present the results for the Galactic models. The details of the Galactic models can be found in Kanbur et al. (2004). The preliminary results for the LMC models are presented in Figure 4. From these figures, we found that:

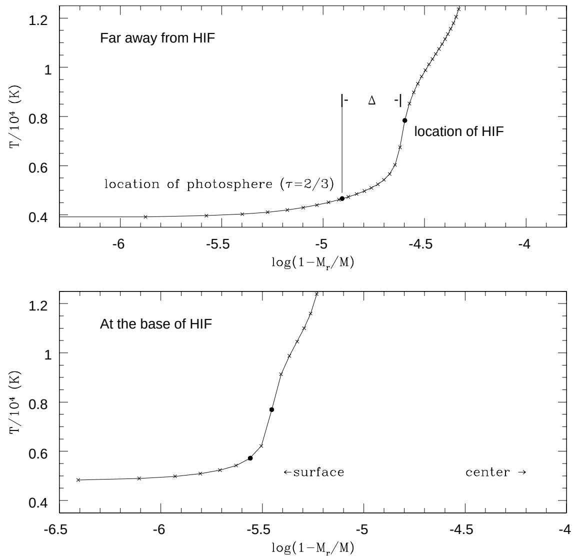

Figure 2. Illustration of the HIF-photosphere interaction, where the temperature is plotted against the mass distribution ($\log[1 - M_r/M]$, where M_r is the mass beneath the radius r and M is the total mass of the star). The crosses represent the zones in the models and the filled circles are the locations of the HIF and photosphere. The Δ is the 'distance' between the HIF and the photosphere. In the top panel, the photosphere is far away from the HIF and there is no interaction at all. In the bottom panel, the photosphere is located at the base of the HIF, where the interaction takes place.

1. At maximum light, the photosphere is close to the base of the HIF for both of the Galactic and the LMC models, hence the photosphere–HIF interaction could occur. This is verified by the empirical studies that the PC(max) relation is flat (Simon et al. 1993; Kanbur & Ngeow 2004; Kanbur et al. 2004).

2. However, there is a clear difference at minimum light between the Galactic and the LMC models: the photosphere for the LMC models are closer to the HIF at minimum light (hence smaller Δ), thought it starts to move away from the HIF at $\log(P)$ ~1.30. In contrast, the photosphere for the Galactic models are far away from the HIF, hence there is no interaction occurring at minimum light for the Galactic Cepheids.

3. These results are, to a large extent, independent of the ML relation used in the models, as the models with the two ML relations agree well with each others.

In conclusion, the different behaviour of the HIF–photosphere interaction between the Galactic and the LMC models could be the reason for the break we see

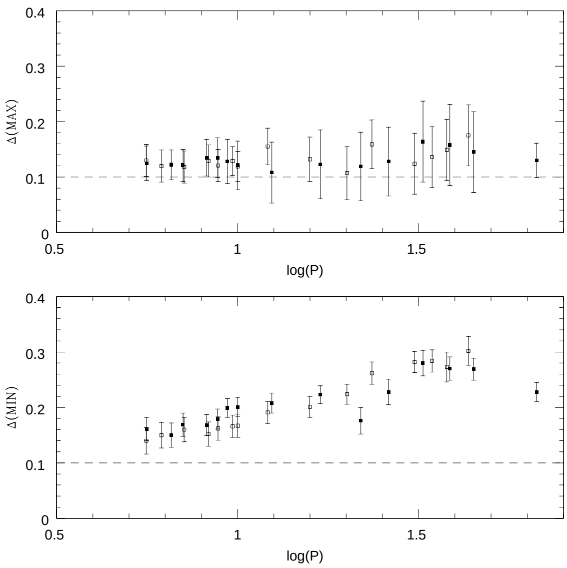

Figure 3. The ‘distance’ between the HIF and photosphere (in mass distribution) for the Galactic models at maximum and minimum light as a function of pulsation period. The open and closed squares are the models with Bono et al. (2000) and Chiosi (1989) ML relation, respectively. The dashed lines represent (roughly) the outer boundary of the HIF.

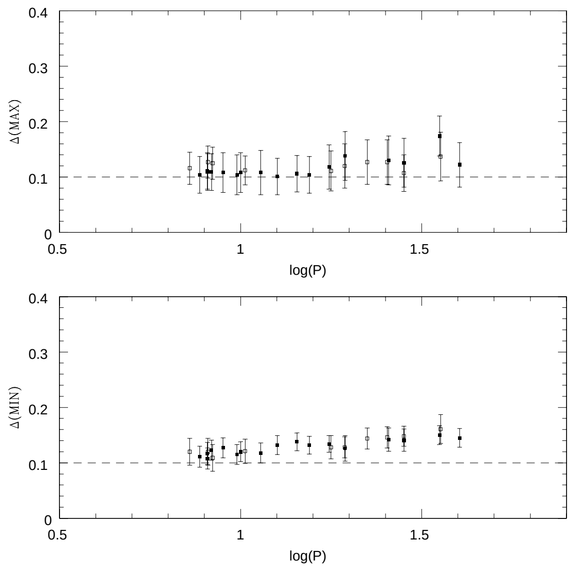

Figure 4. Same as for Figure 3, but for the LMC models.

in the LMC PL and PC relations. Details of this study are still in-progress. The multi-band observations of Gaia of all of the Galactic Cepheids and the LMC Cepheids could provide further constraints to the theoretical studies. The accurate PC and PL relations (with parallax measurements to the Galactic Cepheids) measured from the Gaia mission are essential and important for future stellar pulsation and distance scale studies.

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