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Age dependence of the vertical distribution of Cepheids

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Abstract. The wavelike oscillations of the vertical scale height of the local population of classical Cepheids located at Galactocentric distances $R_0 - 1\,\mathrm{kpc} < R_g < R_0 + 1\,\mathrm{kpc}$ is analyzed using Cepheid ages computed in terms of evolutionary models of Pols et al. (1998) with and without the allowance for convective overshooting. The resulting periods of vertical oscillations of stars about the galactic plane are found to be $P_Z = 74 \pm 2$ Myr and $P_Z = 104 \pm 2$ Myr for standard models and models with overshooting, respectively. If interpreted as a manifestation of vertical virial oscillations, the pattern found implies local mass density values of $\rho_{std} = 0.118 \pm 0.007\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ and $\rho_{ovs} = 0.060 \pm 0.004\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$, respectively. The latter value is totally incompatible with recent estimates based on Hipparcos data and the former value, combined with recent estimates of the local density of visible matter, sets an upper limit of $0.023\,\mathrm{M}_\odot\,\mathrm{pc}^{-3}$ for the local density of dark matter.

1. Introduction

Almost 30 years ago Joeveer (1974) found the dispersion of vertical coordinates (σZ) of Galactic classical Cepheids to vary non-monotonically with age (inferred from period) in a wavelike pattern. He interpreted these oscillations as a manifestation of the fact that each subpopulation of coeval Cepheids is not in vertical virial equilibrium, i.e., that the mean initial (vertical) velocities and coordinates of stars are not perfectly balanced. This causes the stars at a certain Galactocentric distance to recede from and approach the Galactic plane in a correlated way with a period (frequency) determined by local mass density (and therefore the same for all stars at a given distance from the Galactic center). Joeveer (1974) used the period of vertical oscillations of Galactic Cepheids thus determined to estimate the local mass density in the solar neighborhood.

However, unlike Joeveer (1974), we consider our primary task to be not to determine local mass density, which we believe to be much better constrained by recent kinematic analyses and therefore already known, but to use this already known density to discriminate between two evolutionary grids (Pols et al. 1998) that are identical in all respects except that one is computed with, and another without, the allowance for convective overshooting (these two grids, naturally, yield different Cepheid ages and, consequently, different periods of vertical oscillations of the Cepheid population).

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2. Basic formulas

Consider a Cepheid located in the vicinity of the Galactic plane. If the Cepheid has a close-to-circular velocity in the Galactic plane and small vertical velocity, its vertical motion is, to a good approximation, decoupled from the motion parallel to the Galactic plane and obeys the following equation:

$$dZ^2/dt^2 + \omega_z^2 \cdot Z = 0 \tag{1}$$

(see, e.g., King 1994), where ω_z ($=2\pi/P_z$) is the frequency (and P_z, the period) of vertical oscillations determined by local mass density and rotation- curve parameters via the Poisson equation:

$$(\omega_z)^2 + (d^2\Phi/dR^2) + (1/R)(d\Phi/dR) = 4\pi G\rho. \tag{2}$$

The sum of the last two terms in the left-hand side of the above equation can be easily expressed in terms of the local values of Oort's constants A and B:

$$(d^2\Phi/dR^2) + (1/R)(d\Phi/dR) = -2 \cdot (A^2 - B^2) \tag{3}$$

and shown to be negligible compared to $4\pi G\rho$. Young objects are close to the Galactic plane and therefore for Cepheids located within a narrow interval of Galactocentric distances $\rho \sim$ constant and the general solution to equation (1) – harmonic oscillations with frequency ω_z – has the following form:

$$Z = Z_0\cos(\omega_z t) + (V_{Z(0)}/\omega_z)\sin(\omega_z t), \tag{4}$$

where Z_0 and $V_Z(0)$ are the initial vertical coordinate and vertical velocity component, respectively. It can be easily shown that:

$$(\sigma Z)^2 = (1/2)((\sigma V_{Z(0)})^2 + (P_Z\sigma V_{Z(0)}/2\pi)^2)+$$

$$(1/2)((\sigma V_{Z(0)})^2 - (P_Z\sigma V_{Z(0)}/2\pi)^2)\cos(4\pi/P_Z t) \tag{5}$$

$$+(1/2)(rP_Z\sigma Z_0\sigma V_{Z(0)}/2\pi)\sin(4\pi/P_Z t).$$

Here r is the coefficient of correlation between the initial vertical coordinates and initial vertical velocity components.

Thus by analyzing the dependence of *observed* $(\sigma Z)^2$ on age t (*computed in terms of a certain evolutionary grid*), one can infer the period P_Z of vertical oscillations (which is equal to two periods of the variation of $(\sigma_Z)^2$) and hence the *local mass density* ρ_0 that the period implies via the Poisson equation. A comparison of the local mass densities ρ_0 thus inferred with the local mass density values based on recent analyses of stellar kinematics allows one to discriminate between *different evolutionary grids* which, naturally, yield different individual Cepheid ages, and, consequently, different periods P_Z.

3. Data

We adopted the fundamental periods and heliocentric distances of Cepheids from the Catalog of Cepheid light-curve parameters by Berdnikov et al. (2000) and computed the Cepheid ages using the following period-age relations:

$$\log t_{std} = 8.32 - 0.63 \cdot \log P \tag{6}$$

and

$$\log t_{ovs} = 8.49 - 0.66 \cdot \log P \tag{7}$$

derived by fitting the period-color and period luminosity relations of Berdnikov et al. (1996) to the evolutionary grids of Pols et al. (1998) without and with convective overshooting, respectively.

4. Results

Fig. 1(ab) shows how the dispersion of vertical coordinates of Cepheids with heliocentric distances $r < 2.5$ kpc located at within Galactocentric distances $R_0 - 1\,\mathrm{kpc} < R_g < R_0 + 1\,\mathrm{kpc}$ depend on age computed in terms of evolutionary grids without and with convective overshooting, respectively. The periods of these oscillations are equal to

$$P_{std} = 37 \pm 1\,\mathrm{Myr} \tag{8}$$

and

$$P_{ovs} = 52 \pm 2\,\mathrm{Myr} \tag{9}$$

The corresponding periods P_Z of vertical oscillations are

$$P_{Z(std)} = 74 \pm 2\,\mathrm{Myr} \tag{10}$$

and

$$P_{z(ovs)} = 104 \pm 4\,\mathrm{Myr}, \tag{11}$$

implying local mass densities of $\rho_{0(std)} = 0.118 \pm 0.007\,\mathrm{M_\odot\,pc^{-3}}$ and $\rho_{0(ovs)} = 0.060 \pm 0.004\,\mathrm{M_\odot\,pc^{-3}}$, respectively. According to recent estimates based on Hipparcos data, the local dynamical (total) mass density and the local density of visible matter are equal to:

$$\rho_{0(dyn)} = 0.102 \pm 0.010\,\mathrm{M_\odot\,pc^{-3}} \tag{12}$$

and

$$\rho_{0(vis)} = 0.095\,\mathrm{M_\odot\,pc^{-3}}, \tag{13}$$

respectively (Holmberg & Flynn 2000). It thus follows that evolutionary grids with strong convective overshooting yield Cepheid ages that are totally incompatible with the known local mass density and it appears that standard evolutionary grids should be preferred (see Fig. 2). This result agrees excellently what was obtained by applying the same technique to the vertical coordinates of local young open clusters (Dambis 2003). Combined with the estimate of the local density of visible mass mentioned above, the result obtained can be used to impose an upper limit for the local density of dark mass:

$$\rho DM \leq \rho_{std} - \rho_{vis} = 0.023\,\mathrm{M_\odot\,pc^{-3}}. \tag{14}$$

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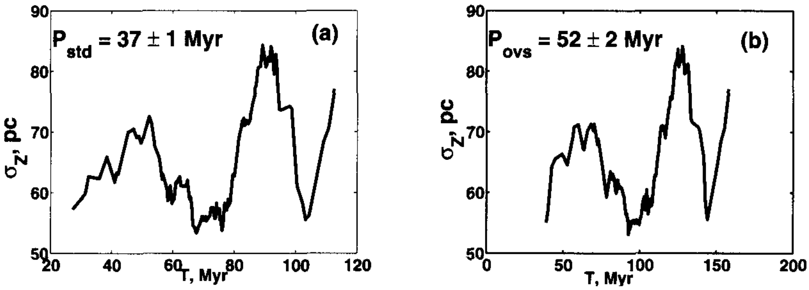

Figure 1. Vertical dispersion of the Cepheid layer as a function of age: standard models (a) and models with overshooting (b).

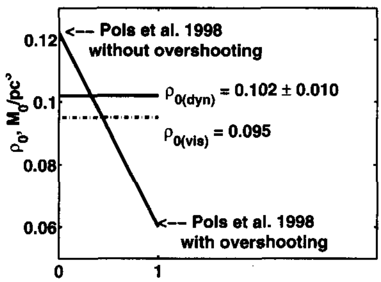

Figure 2. Local mass density as a function of "overshooting index".

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