AGE DEPENDENCE OF THE VERTICAL DISTRIBUTION OF
YOUNG OPEN CLUSTERS: IMPLICATIONS FOR LOCAL
MASS DENSITY, STELLAR EVOLUTION, AND STAR
FORMATION

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Abstract. The ages of 203 open clusters from the list of A.K.Dambis [1999] are computed in terms of Cambridge evolutionary tracks with and without the allowance for convective overshooting (Pols et al. [1998]). The vertical scaleheight of the cluster layer for 123 objects at Galactocentric distances $R_0-1$ kpc $< R_g < R_0+1$ kpc is found to vary nonmonotonically with age exhibiting a wavelike pattern similar to the one earlier found for the Cepheid population (Joeveer [1974]). The period of these variations is equal to $P_Z = 74 \pm 2$ Myr and $P_Z = 92 \pm 2$ Myr if cluster ages are computed in terms of evolutionary models of Pols et al. [1998] without and with overshooting, respectively. If interpreted as a manifestation of vertical virial oscillations, the implications of the pattern found are threefold: (1) the period of vertical oscillations can be reconciled with the known local density of visible matter only if cluster ages are computed with no or just mild overshooting ($P_Z = 74 \pm 2$ Myr implies a maximum local density of $\rho = 0.118 \pm 0.006 M_\odot pc^{-3}$ compared to $\rho = 0.102 M_\odot pc^{-3}$ recently inferred from Hipparcos data (Holmberg & Flynn [2000]), whereas the period implied by the ages computed using models with overshooting ($P_Z = 92 \pm 2$ Myr) implies a maximum local density of only $\rho = 0.075 \pm 0.003 M_\odot pc^{-3}$ and is thus totally incompatible with recent estimates, (2) there is no much room left for the dark matter ($\rho_{DM} \leq 0.027 M_\odot pc^{-3}$ in the Galactic disk near the solar Galactocentric distance, and (3) at the time of their formation open clusters have, on the average, excess kinetic energy (in the vertical direction) and as a population are not in virial equilibrium; moreover, the initial vertical coordinates of open clusters (at the time of their birth) are strongly and positively correlated with initial vertical velocities (the correlation coefficient is $r(Z_0, V_2(0)) = 0.81 \pm 0.08$), thus favoring a scenario where star formation in the disk is triggered by some massive objects falling onto the Galactic plane.

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1 Introduction

Almost 30 years ago Joeveer (1974) found the dispersion of vertical coordinates ($\sigma Z$) of Galactic classical Cepheids to vary nonmonotonically 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.

Here we analyze the evolution of the vertical distribution of another class of young Galactic-disk objects with accurately determinable ages -- open star clusters. 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 cluster ages and, consequently, different periods of vertical oscillations of the cluster population).

2 Basic formulas

Consider an open cluster located in the vicinity of the Galactic plane. If the cluster 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:

$$\frac{dZ^2}{dt^2} + \omega^2 Z = 0$$

(see, e.g., King 1997), where $\omega_z (=2\pi/P_z)$ is the frequency (and $P_z$, the period) of vertical oscillations determined by local mass density and rotation-curve parameters via the Poisson equation:

$$(\omega_z)^2 + \left(\frac{d^2\Phi}{dR^2}\right) + \left(\frac{1}{R}\right)(d\Phi/dR) = 4\pi G\rho.$$  (2.2)

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 $B$:

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

(2.3)

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

$$Z = Z_0 \cos(\omega_z t) + \left(\frac{V_{Z(0)}}{\omega_z}\right) \sin(\omega_z t),$$

(2.4)

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

$$(\sigma Z)^2 = \left(1/2\right)\left[\left(\sigma V_{Z(0)}\right)^2 + \left(P_Z \sigma V_{Z(0)} / 2\pi\right)^2\right] + \left(1/2\right)\left[\left(\sigma V_{Z(0)}\right)^2 - \left(P_Z \sigma V_{Z(0)} / 2\pi\right)^2\right] \cos\left(4\pi / P_Z t\right)$$

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

(2.5)

It thus follows that by analyzing the dependence of observed $(\sigma Z)^2$ on age $t$ computed in terms of a certain evolutionary grid we can infer four very interesting parameters. First, the period $P_Z$ of vertical oscillations (e.g., by power-spectrum analysis as is usually done in variable-star research) and the local mass density $\rho_0$ it implies via Poisson equation. Second and third, the initial dispersion of vertical coordinates $(\sigma Z_0)$ and vertical velocity components $(\sigma V_{Z(0)})$. And, fourth, the correlation coefficient $r$ between the initial vertical coordinate and vertical velocity. And, finally, by comparing the local mass densities $\rho_0$ thus inferred with the local mass density values based on recent analyses of stellar kinematics we can discriminate between different evolutionary grids which, naturally, yield different individual cluster ages, and, consequently, different periods $P_Z$.

3 Initial data

Our initial sample consisted of the catalog of 203 young open clusters with heliocentric distances and ages determined in a homogeneous way from published $UBV$ photoelectric or CCD photometry (Dambis 1999) using Kholopov’s (1980) empiric ZAMS and isochrones by Maeder & Meynet (1991). Since one of the principal aims of this work is to choose between stellar models with and without convective overshooting, we first converted our cluster ages to two age scales determined by the evolutionary grids of Pols et al. (1998) computed with and without overshooting.

4 Evolution of vertical dispersion

Figure 1 shows the variation of the ‘sliding dispersion’ $\sigma Z$ as a function of mean age $t$ for clusters located within the Galactocentric distance interval from $R_0 - 1$ kpc to $R_0 + 1$ kpc ($R_0 = 7.5$ kpc (see, e.g., Dambis 2003 and Dambis & Rastorguev 2001) is the Galactocentric distance of the Sun) computed in terms of the evolutionary grid of Pols et al. (1995) without overshooting. Figure 2 shows the corresponding periodogram. Figures 3 and 4 show the corresponding plots for the case where cluster ages are computed in terms of the evolutionary grids of of Pols et al. (1998) with overshooting. The inferred parameters $\sigma Z_0$, $\sigma V_{Z(0)}$, $r(Z_0, V_{Z(0)})$, $P_Z$, 

$\frac{\sigma Z}{\sigma V_{Z(0)}}$.
and $\rho_0$ (computed assuming that $A = +17.0 \text{ km/s/kpc}$ and $B = -11.7 \text{ km/s/kpc}$ - Rastorguev et al. (2001); note that adopting a different pair of reasonable values of $A$ and $B$ based on observations has little effect on the final result - e.g., $\rho_0$ changes by only about 3% if we adopt flat rotation curve with $A + B = 0$.

4.1 Implications for stellar evolution

Figure 5 compares our local mass density values computed in terms of two evolutionary grids with recent estimates based on the analysis of local stellar kinematics and the estimate of the local density of visible mass (Holmberg & Flynn 2000). It is immediately evident from this figure that strong overshooting should be ruled out for stars in young clusters: the local mass density $\rho_0 = 0.075\pm0.003 M_{\odot}/pc^3$ implied by the corresponding grid is inconsistent not only with the total (dynamic) mass density of $\rho_{dyn} = 0.102\pm0.010 M_{\odot}/pc^3$ (Holmberg & Flynn 2000), but even with the density of visible matter $\rho_{dyn} = 0.095 M_{\odot}/pc^3$ (ibid).

4.2 Implications for local mass density

Given that all known departures from standard models of stellar evolution (e.g., mass loss, overshooting) slow down the rate of evolution and, consequently increase the ages and times scales based on these ages, the results summarized in Table 1 lead us to conclude that the local mass density value inferred in terms of evolutionary grids without overshooting should be considered as an upper limit for this parameter. It thus follows that

$$\rho_{\text{max}} = 0.118 \pm 0.006 M_{\odot}/pc^3.$$  

4.3 Implications for local dark mass

Given the estimate of local density of visible mass ($\rho_{\text{vis}} = 0.095 M_{\odot}/pc^3$) mentioned above and the upper limit for the total local mass density just obtained, we find that the local density of dark mass cannot exceed

$$\rho_{DM} \leq \rho_{\text{max}} - \rho_{\text{vis}} = 0.027 M_{\odot}/pc^3. \quad (4.1)$$

4.4 Implications for star formation

Two conclusions concerning star formation can be drawn from Figs 1 and 3 and Table 1. First, the population of open clusters at the time of birth is overheated (i.e., has excess kinetic energy) in the vertical direction: one can see that the layer of newly-born clusters expands immediately after age zero. And second, there is strong positive correlation (with a correlation coefficient of 0.8) between the initial vertical coordinates of newly-born clusters and the initial vertical velocities. The two results combined favor scenarios where star formation is triggered by impacts of some massive bodies onto the Galactic plane.
Fig. 1. Variation of the dispersion of vertical coordinates ($\sigma_Z$) of young open clusters as a function of age computed in terms of models of Pols et al. (1998) with overshooting.

Fig. 2. Power spectrum of the variation of squared vertical coordinate $z^2$ with cluster ages computed in terms of models of Pols et al. (1998) with overshooting. $P_Z = 92 \pm 2$ Myr.

Fig. 3. Variation of the dispersion of vertical coordinates ($\sigma_Z$) of young open clusters as a function of age computed in terms of models of Pols et al. (1998) without overshooting.

Fig. 4. Power spectrum of the variation of squared vertical coordinate $z^2$ with cluster ages computed in terms of models of Pols et al. (1998) without overshooting. $P_Z = 74 \pm 2$ Myr.

Fig. 5. Local mass density implied by the frequency of oscillations of the dispersion of vertical cluster coordinates ($\sigma_Z$) as a function of "overshooting index".
Table 1. Initial dispersions of vertical coordinates ($\sigma Z_0$) and velocities ($\sigma V_{Z(0)}$) of young open clusters, the correlation coefficient $r$ between $Z_0$ and $V_{Z(0)}$, period $P_Z$ of vertical oscillations, and the implied local mass density (models of Pols et al. [1998] without (STD) and with (OVS) overshooting).

| Models | $\sigma Z_0$ (pc) | $\sigma V_{Z(0)}$ (km/s) | $r$ | $P_Z$ (Myr) | $\rho_0$ ($M_\odot$/pc$^3$) |
|--------|-------------------|--------------------------|-----|-------------|------------------|
| STD    | 40                | 4.3                      | 0.81| 74          | 0.118            |
|        | $\pm 2$           | $\pm 0.4$                | $\pm 0.08$ | $\pm 2$ | $\pm 0.006$    |
| OVS    | 42                | 3.3                      | 0.87| 92          | 0.075            |
|        | $\pm 2$           | $\pm 0.3$                | $\pm 0.08$ | $\pm 2$ | $\pm 0.003$    |

Another interpretation may involve vertical motions triggered by with spiral density waves (see, e.g., Fridman et al. [1998] who found vertical velocities in the spiral galaxy NGC 3631 to be correlated with the arrangement of spiral arms).

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