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Effects of stellar rotation on age determination from Strömgren photometry

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Abstract. The effects of stellar rotation on the photometric derivation of atmospheric parameters, ages and masses of main sequence B7-A4 stars are evaluated. *Monte-Carlo* simulations, used to generate a sample in the mass range 1-5 $M_\odot$ with all necessary individual rotational parameters and fundamental quantities, and the corrections on the photometric indices proposed by Collins & Sonneborn (1977), provide an approximate quantification of the differences between true parameters and those obtained with classical procedures in which the effects of stellar rotation on photometric indices are ignored. Mean statistical corrections to the photometric indices related to temperature as a function of $(v \cdot \sin i)$ are proposed. The results obtained indicate that stellar main-sequence ages are clearly enhanced by an average 30-50% when rotation is not considered whereas mass changes are, in practice, below the mean error level. We conclude that rotation effects on the photometric indices should be taken into account in general studies of galactic evolution in which young stars are involved.

Key words: stars: fundamental parameters – stars: rotation – stars: early type – techniques: photometric

1. Introduction

To study the kinematical behaviour of young stars in the solar neighbourhood, and to advance in our understanding of phenomena such as the existence and origin of moving groups (Chen et al., 1997), the origin and evolution of the Gould Belt (Comerón and Torra, 1994) or the change of vertex deviation with age (Moreno, 1996), among others, we have developed an algorithm to determine atmospheric parameters and ages from Strömgren photometry (Figueras et al., 1991; Asiain et al., 1997). Our algorithm, similar to other procedures used when large number of stars are involved, ignores the fact that rotational equatorial velocities of normal main sequence stars in the B-A spectral range can reach values up to 300-400 km s^{-1} (Wolff et al., 1982) and so their Strömgren colour indices are severely affected. Furthermore, bearing in mind that the Hipparcos mission may improve the accuracy of the astrometric parameters and space velocities, complementary work to determine the individual physical parameters of the stars and to evaluate the systematic errors on ages induced by the effect of stellar rotation is necessary.

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In this paper we present a first attempt to evaluate these effects. We will consider only the effects of rotation on the stellar atmospheres, letting aside its possible evolutionary effects, so ignoring that, at least at high rotation rates, the structure and other induced processes in the interior of the star would also be affected. Although this simplification and the fact that the models used to attain our objectives are old (Collins and Sonneborn (1977) corrections computed from Kurucz (1970) are the only available tabulations on Strömgren photometric indices) the quantitative results obtained can be used in future work on galactic structure and kinematics.

In Sect. 2, we present the method used in this work, results are discussed in Sect. 3.

2. Simulation of a main sequence stars sample

Using a *Monte-Carlo* simulation, we have generated a sample of 10000 Main Sequence stars with the masses in the range $m \in [2, 5]M_\odot$ and the ages within the MS lifetime. The range of masses considered has been imposed by the high mass limit of the Faulkner et al. (1968) rotating interior models (1 to 5 solar masses) and, at lower masses, by the inconsistency observed in the use of the Collins & Sonneborn (1977) rotation corrections – hereafter CS77 – simultaneously with the empirical calibration of the photometric $uvbyH_\beta$ *grids* performed by Moon & Dworetsky (1985).

To generate ages and masses, the *Present Day Mass Function* (PDMF) of Scalo (1986), a constant Star Formation Rate and the set of stellar evolutionary models of Schaller et al. (1992) with Z = 0.02 have been considered. The interpolation procedure described in Asiain et al. (1997) has been applied to determine their atmospheric parameters – effective temperature and surface gravity – and from them and the calibrated *grids* of

Moon and Dworestsky (1985) their corresponding Strömgren colour indices. This first set of colour indices corresponds to the colours expected when stars are not rotating. A second set of photometric indices is built taking into account the effects of rotation on the stellar atmosphere. To do so, for each star we have used a *Monte-Carlo* simulation to generate two rotational parameters: the equatorial velocity v and the inclination of the rotation axis with respect to the visual line i. The set of parameters generated are then used to interpolate in the CS77 tables to determine the Strömgren colour indices. Comparing these two sets of colours enable us to estimate the effects of rotation on the colours of a stellar population. Moreover, one can apply to the second set of photometric indices the classical procedures, neglecting the effects of rotation, to derive the atmospheric parameters, the masses and the ages. The differences between the *true* values, known by construction, and the so derived values give an estimate of the error made on various physical quantities when the effects of rotation on the photometric indices are neglected.

In the following we present the probability functions adopted in the present work and the main hypotheses considered in performing the simulation.

2.1. Ages and masses

The PDMF (*Present Day Mass Function*) $\phi(\log m)$ of Scalo (1986) – interpolated linearly in our whole simulation range – and a constant Star Formation Rate have been considered. The variation of the MS lifetime ($\tau(m)$) with mass has been adopted from the Schaller et al. (1992) stellar evolutionary models with Z=0.02 and hence $t \in [0, \tau(m)]$.

2.2. Rotation parameters

A Maxwell-Boltzmann distribution function for the equatorial velocities has been adopted which, although it is the simplest, seems to fit many of the histograms of field star samples. We have included the variation of the mean equatorial velocities with the stellar mass by means of the dispersion parameter $s(m)$. Thus:

$$f(v;s)\,dv \;=\; \sqrt{\frac{2}{\pi}}\,\frac{v^2}{s^3}\,e^{-\frac{v^2}{2s^2}}\,dv \quad .$$

We adopt the hypothesis that the equatorial velocity and the inclination angle are independent. Isotropy in the rotation axes direction is also adopted (Gray, 1976 and Chandrasekhar & Münch, 1950), which is provided by the lack of correlation observed between the projected rotational velocities and the galactic coordinates for a number of field star samples. Then, the distribution function of the angle of inclination becomes

$$\zeta(i)\,di \;=\; \sin i\,di \quad .$$

with i ranging between 0 and $\pi/2$. Following Chandrasekhar & Münch (1950), the true velocity distribution $f(v)$ can be related to its observable counterpart $\phi(v \cdot \sin i)$ by the following expression between their first order moments:

$$< v > = \frac{4}{\pi} < v \cdot \sin i > \quad .$$

Table 1. Adopted values of the maxwellian parameter s – computed by us from mean $v \cdot \sin i$ (Schmidt-Kaler, 1982) – and critical velocity v_c (from Faulkner et al., 1968, models) as a function of mass m. Units: solar masses and km s^{-1}.

m	s	v_c
5.0	147	526
4.0	149	504
3.0	130	477
2.5	113	460
2.0	105	441
1.7	90	428

This expression has been used to set values to the maxwellian parameter $s(m)$ as a function of the mass of the star (see Table 1). Several empirical evaluations of the variation of the projected equatorial velocities as a function of the spectral type have been performed since the nineteen twenties. Here we have chosen the mean $< v \cdot \sin i >$ quoted by Schmidt-Kaler (1982), and we have related spectral type and mass for the main sequence stars from CS77.

At this stage we have thus a sample of main sequence stars with known masses, ages, equatorial velocities and inclination angles. To associate photometric indices to each star, we shall use the tables given by CS77. However in these tables the photometric indices are given as a function of spectral type, inclination angle and $\omega = \Omega/\Omega_c$ (the so called *fractional* angular velocity, where Ω_c is the breaking angular velocity). To relate our equatorial velocities with ω, we used the stellar models of Faulkner et al. (1968), which provide values of mean stellar radii for various masses and rotational velocities up to the critical velocity. Although CS77 had used the interior models by Sackmann & Anand (1970) in their calculations, it can be shown that there are no significant differences (see for example Endal & Sofia, 1976). It has to be mentioned that Faulkner et al. (1968) models are for Zero Age Main Sequence stars, so we are not considering that the relation linking the mass and the breaking equatorial velocity varies during the evolution due to the expansion of the envelope.

Knowing the mass and the equatorial velocity of each simulated star, we have computed its equatorial radius, the angular velocity Ω and the critical value Ω_c, so clearly:

$$\omega \;=\; \omega(m, v) \quad .$$

Because every rotating model has its own critical velocity value given by $\Omega_c(m)$, the simulation of the equatorial velocities should be performed inside the corresponding allowed ranges (see Table 1). The distribution of the *fractional* angular velocity and the $\omega - v$ relation obtained for our simulated sample are presented in Fig. 1.

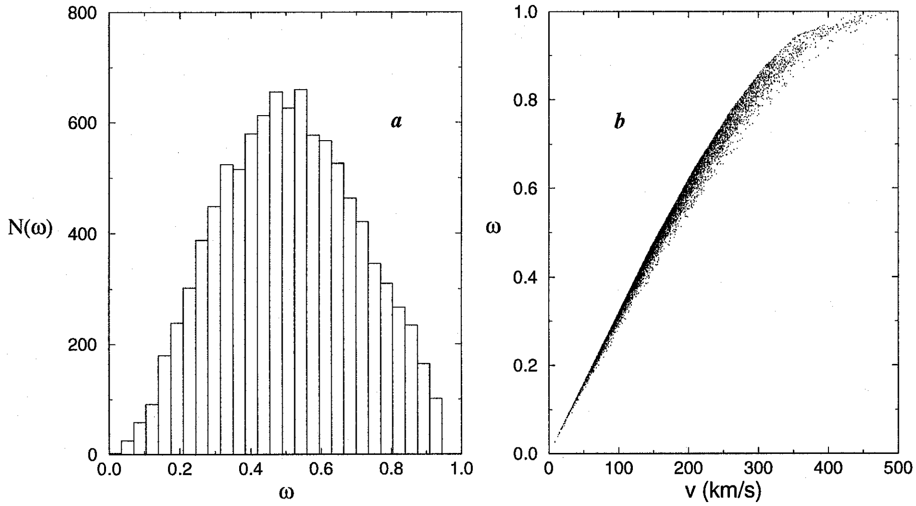

Fig. 1. a Distribution of the whole sample fractional angular velocity ω. **b** $\omega - v$ relation (Faulkner et al., 1968, models were used).

2.3. Photometric colours

To calculate the atmospheric parameters of each simulated star from its mass and age (with a fixed metallicity of Z = 0.02) we used the set of stellar evolutionary models of Schaller et al. (1992) and the interpolation procedure described in Asiain et al. (1997). From these, the photometric indices were computed using the 2D *grids* of Moon & Dworetsky (1985), and the procedure of interpolation given by Napiwotzki *et al.* (1993) and discussed in Masana (1994). This provides the basic pair of colours, say (c_0, β) or (a_0, r), the former for stars classified as belonging to photometric region I (with $T_{eff} > 11000$ K, called early group by Strömgren, 1966) and the second to region II ($T_{eff} \in [8500, 11000]$ K, called intermediate group). c_0 and a_0 are good temperature indicators while β and r are related to luminosity (and hence surface gravity).

2.4. Application of CS77 corrections

Collins & Sonneborn (1977) published the most extensive tabulations of the basic Strömgren colours jointly with the H_β index (Crawford & Mander, 1966) in the MS B0 to F8 spectral range and for several values of the rotational parameters. They fit model atmospheres supplied by the ATLAS code (Kurucz, 1970) to different locations at the stellar surface, defined by their local T_{eff} and $\log g$ (the local effective temperature was obtained by means of the *von Zeipel theorem*). The spectral intensities were integrated over the visible stellar hemisphere (for the aspect angles i: 0, 30, 45, 60 and 90°) and the resulting monochomatic fluxes convolved with the filter transmission functions to yield the $(b-y)$, c_0, m_0 and β indices. All this work was carried out for a set of different combinations of the rotation parameter ω and i. For the last spectral types the calculations were made only for low and moderate rotation rates because of the clear drop of the observed $< v \cdot \sin i >$.

The static models (those with ω = 0) allow us to determine a complete set of *photometric corrections* applicable over the MS domain as follows:

$$\Delta(b-y)^{[\omega,i]} = (b-y)^{[\omega,i]} - (b-y)^{\omega=0}$$

$$\Delta c_0^{[\omega,i]} = c_0^{[\omega,i]} - c_0^{\omega=0}$$

$$\Delta m_0^{[\omega,i]} = m_0^{[\omega,i]} - m_0^{\omega=0}$$

$$\Delta \beta^{[\omega,i]} = \beta^{[\omega,i]} - \beta^{\omega=0}$$

Δc_0 and $\Delta\beta$ were used for stars belonging to the early group and the corrections for the intermediate group were computed as follows:

$$\Delta a_0 = 1.36\,\Delta(b-y) + 0.18\,\Delta c_0 + \Delta m_0$$

$$\Delta r = -0.07\,\Delta(b-y) + 0.35\,\Delta c_0 - \Delta\beta$$

As the CS77 static models give a mean Teff and mass for each spectral type on the Main Sequence, we have interpolated their tables using the effective temperature of the simulated star deduced from the stellar evolutionary models. The results do not disagree with those derived when using an alternative parametrization (for instance on stellar mass), the difference is below the significance level defined by the typical photometric errors.

At this point of the simulation we know, for each star, the true fundamental and atmospheric parameters and the colour indices we would obtain observationally when the rotation is present. The common procedure that is used to derive physical parameters from Strömgren photometry (Figueras et al., 1991), does not take into account the rotation effects, so the colour indices affected by rotation are used to derive the physical parameters. To reproduce this scheme for our simulated stars, we have derived a T'_{eff}, $\log g'$, m' and t' (the age) from the colours affected by rotation using, as before, the *grids* of Moon & Dworetsky (1985) and stellar evolutionary models of Schaller et al. (1992).

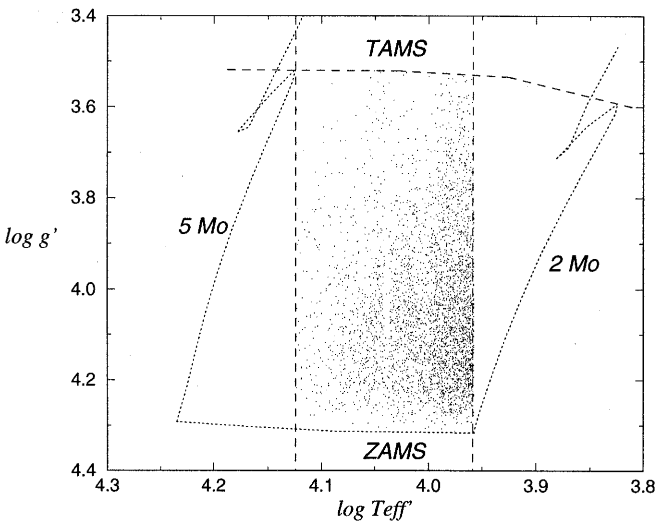

Fig. 2. MS selected subsample.

3. Results

The statistical effects of stellar rotation on a large sample of Main Sequence young stars has been studied at three levels: the photometric indices, the atmospheric parameters and, finally, masses and ages.

From the simulated sample, we selected a subsample cut on effective temperature affected by rotation, T'_{eff} (Fig. 2). This is done to reproduce, as far as possible, some cases from the literature: samples selected according to colour indices or effective temperatures. The limits are 9100 K $< T'_{eff} <$ 13300 K (spectral type between B7-A4 approximately) and they have been fixed by our simulated mass range. The cool limit is fixed by the T_{eff} of the beginning of the H-burning phase of the track at 2 $M_{\odot}$, and the hot limit by the point with the lowest T_{eff} on the Main Sequence evolution of the track at 5 $M_{\odot}$. We have calculated that the percentage of stars with true masses greater than 5 $M_{\odot}$ (not simulated) that could be placed inside our range would be less than 0.7 %. Our subsample contains 3646 stars.

3.1. $uvbyH_{\beta}$ colours

Fig. 3 plots the photometric effects against projected velocities $v \cdot \sin i$. The quadratic trend observed was first noticed by Sweet & Roy (1935) and confirmed by several authors (Guthrie, 1987). For the two photometric regions, the indices related to temperature have more significant effects than the luminosity indices, with 77% of stars with $|\Delta c_0| > 2\sigma_{c_0} \simeq 0.04^m$ and 27% with $|\Delta a_0| > 2\sigma_{a_0} \simeq 0.04^m$. These limits were chosen to account for typical photometric errors and uncertainties in the unreddening procedures. Although there is a clear and systematic gravity effect (reflected in β and r) the corrections are small and we do not propose any fit for them. For the colour indices related to temperature, we carried out two mean square fits of the type $\Delta\mathscr{C} = A(v \cdot \sin i)^2 + B$, where $\mathscr{C}$ represents the colour indices, A is the slope and B the intercept value for the plot $\Delta\mathscr{C}$ *vs.* $(v \cdot \sin i)^2$.

So, when $v \cdot \sin i$ of the star is known, the corrections indicated in Table 2 are proposed.

Table 2. Fits for temperature indices in early and intermediate regions (ρ: correlation coeficient; n: number of stars).

$Corr.$	A	B	ρ	n
Δc_0	$(2.16 \pm 0.05) \cdot 10^{-6}$	0.044 ± 0.002	0.79	1018
Δa_0	$(1.04 \pm 0.01) \cdot 10^{-6}$	0.0104 ± 0.0003	0.85	2947

Table 3. Fits to the effective temperature and surface gravity corrections (e: early group; i: intermediate group).

$\Delta\mathscr{P}(group)$	A	B	ρ	n
$\Delta T_{eff}(e)$	-0.0167 ± 0.0004	-218 ± 16	-0.77	1018
$\Delta T_{eff}(i)$	-0.0187 ± 0.0002	-150 ± 6	-0.85	2947
$\Delta \log g(e)$	$(-2.10 \pm 0.05) \cdot 10^{-6}$	-0.034 ± 0.002	-0.80	1018
$\Delta \log g(i)$	$(-2.92 \pm 0.04) \cdot 10^{-6}$	-0.048 ± 0.001	-0.83	2947

3.2. *Effective temperatures and surface gravities*

From Figs. 4 and 5, one can see that the general effect of rotation is to decrease both effective temperatures and surface gravities. In case of a moderate rotation rate (ω = 0.5) the atmospheric parameters do not suffer an important change ($\Delta T_{eff} \simeq -450$ K and $\Delta \log g \simeq -0.07$dex fixing i = 60° for an A0 star). In the high rotation case (ω = 0.9) the variations are more dramatic, about $-1700\,K$ and -0.4 dex respectively (again for i = 60° and $T_{eff} \simeq$ 10000 K).

The trends observed in the colour indices are reproduced for the atmospheric parameters (say $\mathscr{P}$) (see Fig. 4). A mean square fit of the type $\Delta\mathscr{P} = A(v \cdot \sin i)^2 + B$ is obtained (Table 3). Again, the correction obtained for log g has no statistical meaning in view of the large errors involved in their computation from Strömgren photometry.

3.3. *Derived ages and masses*

Individual ages (t') and masses (m') affected by rotation have been computed from T'_{eff}, log g', using the stellar evolutionary models of Schaller et al. (1992) at solar composition and the interpolation algorithm developed by Asiain et al. (1997). The effect of rotation on these parameters is clearly shown on Fig. 6. Derived masses of rotating stars are systematically lower than actual values but this effect is not very noticeable because of the orientation of the rotational *fans*. These *fans*, defined as in Collins & Smith (1985), are regions of the theoretical HR diagram which extend from the non-rotating location of the star and cover all possible displacements induced by (ω, i) combinations; they lie approximately along the stellar evolutionary tracks so the mean change on masses is not significant (around -2%).

From Fig. 6b and d we can observe that the ages are strongly enhanced due to rotational effects on photometric indices. In

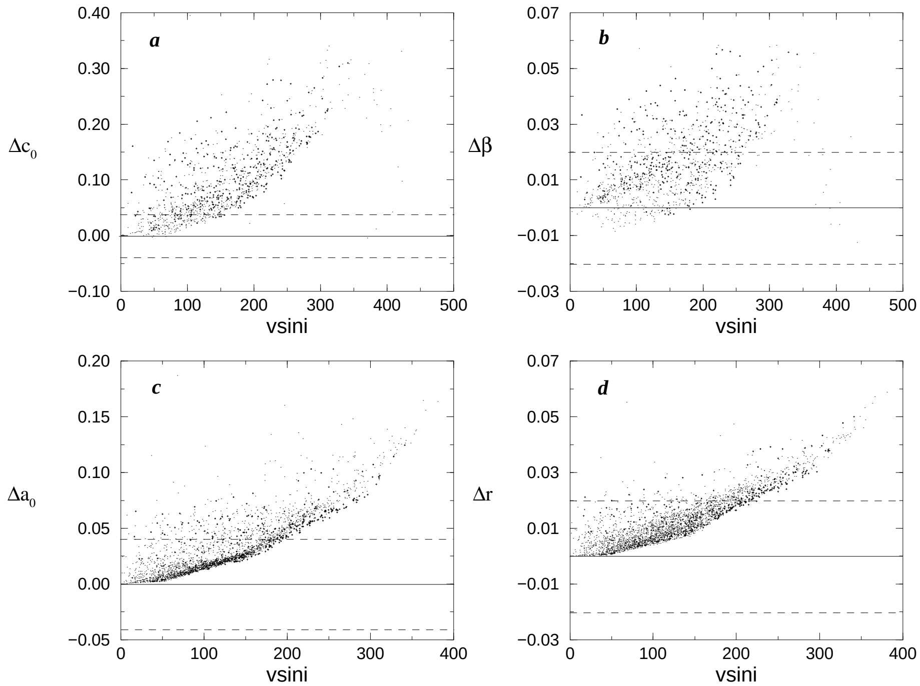

Fig. 3a–d. Effects on the photometric indices (c_0 and β for the early group, a_0 and r for the intermediate group), in the sense *affected by rotation minus true*. Units: magnitudes and km s^{-1}. Dashed lines are estimated uncertainties on the photometric indices considering observational errors and scattering inside the reddening relations.

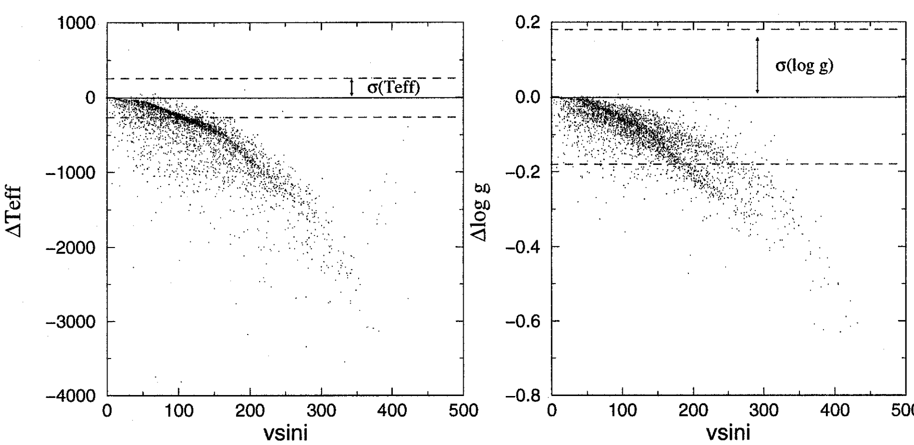

Fig. 4. Effects on the atmospheric parameters T_{eff} and $\log g$ (external errors obtained in Torra et al. (1990) σ_{Teff} = 270 K and $\sigma_{\log g}$ = 0.18 dex are plotted for comparison).

Table 4. Rotation effect on age and mass when bins of *affected* age are considered, being t amd m the true age and mass known from the simulation, t' and m' the age and mass obtained from the photometric indices affected by rotation, $\epsilon(t')$ and $\epsilon(m')$ the errors computed following Asiain et al. (1997) when adopting $\sigma_{T_{eff}}$ = 270 K and $\sigma_{\log g}$ = 0.18 dex, and $\Delta t = t' - t$, $\Delta m = m' - m$. The first line denotes mean values and the second line the corresponding standard deviation. Ages are in units of 10^6 years and masses in $M_\odot$.

$Interval$	n	$<t>$	$<t'>$	$<\epsilon(t')>$	$<\Delta t>$	$<m>$	$<m'>$	$<\epsilon(m')>$	$<\Delta m>$	$<v\cdot\sin i>$
(t')		σ_t	$\sigma_{t'}$	$\sigma_{\epsilon(t')}$	$\sigma_{\Delta t}$	σ_m	$\sigma_{m'}$	$\sigma_{\epsilon(m')}$	$\sigma_{\Delta m}$	$\sigma_{v\cdot\sin i}$
0-100	181	33	72	119	39	2.93	2.88	0.16	-0.05	83
		21	21	74	20	0.44	0.40	0.02	0.07	42
100-200	825	87	156	94	69	2.96	2.88	0.17	-0.08	125
		47	28	77	43	0.59	0.52	0.04	0.17	79
200-300	1068	149	251	85	102	2.69	2.62	0.16	-0.07	126
		68	28	64	65	0.40	0.35	0.03	0.10	68
300-400	1156	222	349	64	127	2.56	2.51	0.17	-0.05	135
		93	28	41	92	0.28	0.25	0.03	0.09	68
400-500	416	280	427	46	147	2.45	2.42	0.17	-0.03	141
		108	17	16	108	0.17	0.13	0.02	0.09	70

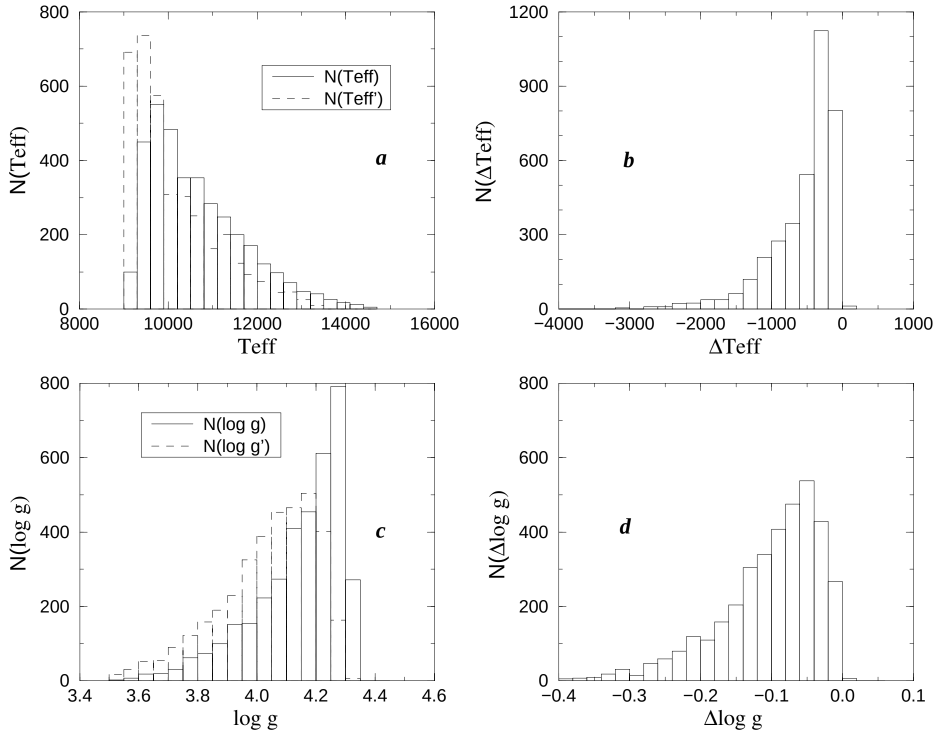

Fig. 5a–d. Histograms of the effective temperature (**a**), surface gravity (**c**) and the resulting corrections (**b,d**), in the sense *affected – true*.

fact, for about the 42% of the selected sample, the age is overestimated by more than $10^8\,years$, a typical value of the MS ages in the mass range considered. We used the algorithm of Asiain et al. (1997) to estimate, for each simulated star, the propagated error on age, $\epsilon(t')$, coming from typical errors on T_{eff} and $\log g$ (we have adopted 270 K and 0.18 dex, respectively (Torra et al., (1990), being these errors induced by the observational errors in the photometric indices and the use of the Moon and Dworetsky (1985) grids). This has allowed us to check for the significance of the derived effects on the age determination. We conclude that for 61% of the stars the error on the age made when neglecting the effect of the rotation on the photometric indices Δt is larger than $\epsilon(t')$, and 34% satisfy $\Delta t > 2\epsilon(t')$.

It is common in studies of galactic kinematics and evolution to divide the star sample into different sets according to the age (for instance in the study of the age-kinematics relation in the solar neigbourhood). In Tables 4 and 5 we have cut our sample into bins of *affected age*, and mean values and standard deviations have been computed. It can be seen that the mean age group is severely affected by rotation, with a systematic effect of 30-50% (Table 5), whereas the effects on mass are less pronounced.

The information given on Table 4 has been displayed on Fig. 7 for visual analysis. The mean true ages $< t > \pm\sigma_t$ are plotted against the affected values $< t' > \pm\epsilon(t')$. The error bars plotted on each axis have different physical meaning: the horizontal error bars correspond to the mean error in the computation of individual affected ages, whereas the vertical bars indicate the dispersion of true ages inside each bin. Except for the earliest bin (where errors and age determination are of the same order) the weight of the rotation effects in the mean age assigned to each group is noticeable, and it should be taken into account in future studies involving age determination from Strömgren photometry.

4. Conclusions

We have used the theoretical rotational corrections on the $uvbyH_\beta$ colour indices proposed by Collins and Sonneborn (1977) to study the effects of stellar rotation on the derivation of atmospheric and fundamental parameters from Strömgren photometry (photometric *grids* and evolutionary models). A simulated sample has allowed us to quantify the effects on main sequence stars in the B7-A4 spectral range, confirming that rotation tends to decrease both the effective temperature and the surface gravity. From the computation of these effects and their comparison with the errors usually involved in the derivation of physical parameters, we conclude that rotational effects should be taken into account in future studies of galactic structure and evolution (Blasi, 1996).

The effects are more pronounced on the photometric indices related to temperature (c_0 and a_0) than those related to gravity (β and r), so some mean statistical corrections are proposed for the former as a function of the projected equatorial velocity ($v \cdot \sin i$). Mean corrections for T_{eff} and $\log g$ have also been computed.

Stellar MS ages in our simulation are clearly enhanced by an average 30-50% when rotation is not considered whereas mass changes are, in practice, below the mean error level, as expected from rotation *fans* extended along the evolutionary tracks. As the rotational equatorial velocities of single normal stars can

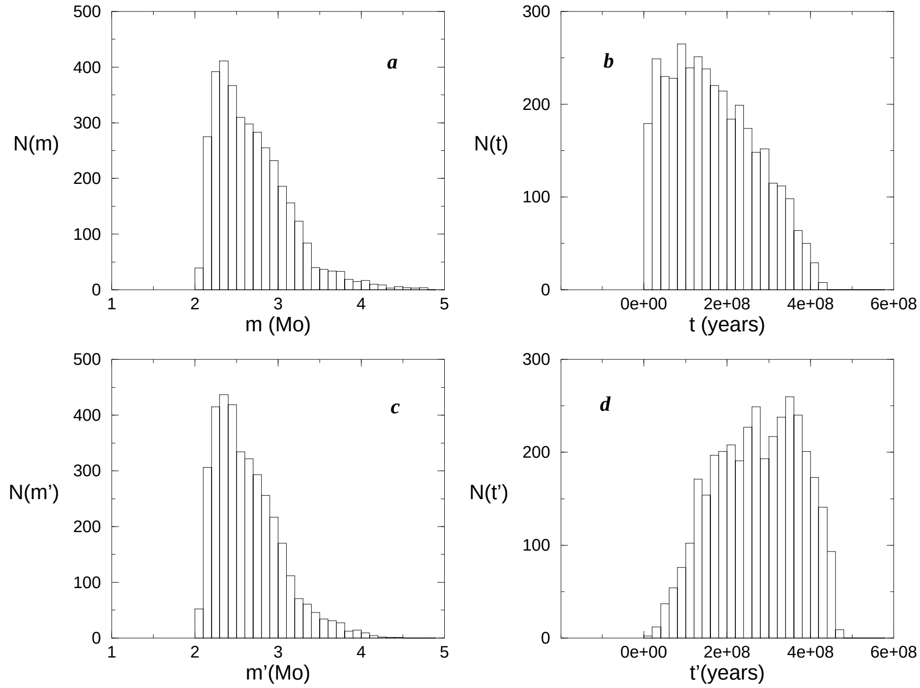

Fig. 6a–d. Mass and age distributions: **a** and **b** true; **c** and **d** affected by rotation.

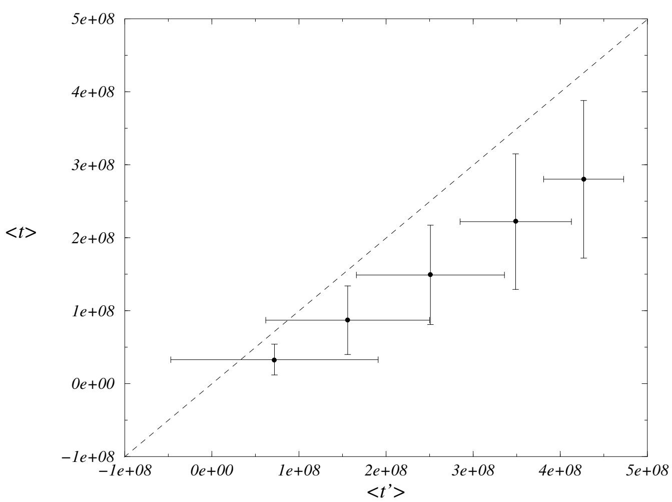

Fig. 7. Mean rotation effect on age determination from Strömgren photometry. See text for explanation.

reach $300 - 400\, km \cdot s^{-1}$ in the B-A Main Sequence spectral range, the stellar rotation effects should be taken into account not just in spectral classification but also in age determination. However, bearing in mind that photometric *grids* and other empirical calibrations (for instance, the unreddening procedures) are probably affected to some extent by all the rotating standard stars included in the samples, more work is needed to derive better corrections in the future.

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Table 5. Relative effects on age and mass (units and notation as in Table 4).

$Interval\,(t')$	$\frac{<\Delta t>}{<t'>}$ (%)	$\frac{<\Delta m>}{<m'>}$ (%)
0-100	54	-1.7
100-200	44	-2.8
200-300	41	-2.7
300-400	36	-2.0
400-500	34	-1.2

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