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Rotation and evolution of A stars: looking for progenitors of cool Ap stars

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Abstract. We explore to what extent the study of the projected rotational velocities of normal A stars might reveal the existence of progenitors of cool Ap stars, i.e. of slowly rotating normal young A stars. Since according to a recent work, magnetic Ap stars with masses ranging from 1.7 to 2.5 $M_{\odot}$ are never found on the ZAMS in the HR diagram, but have completed at least 30% of their MS lifetime, one may suspect that some normal young A stars will become Ap later on. Such progenitors are expected to rotate slowly, as is the case of magnetic Ap stars. We show that an unambiguous proof of their existence would require a much larger sample than is available today.

A sample of A stars with homogeneous determinations of $v \sin i$ and with precise Hipparcos parallaxes is examined. It is shown that no statistically significant difference can be found between the $v \sin i$ distributions of young and old stars, and that the data are compatible with conservation of angular momentum in the case of rigid-body rotation. The $v \sin i$ distribution of young A stars is compatible with a Maxwellian distribution of equatorial velocities, while this is less so of the older A stars.

Key words: stars: chemically peculiar – stars: rotation – stars: evolution

1. Introduction

Slow rotation is one of the main characteristics of Ap stars (Bonsack & Wolff 1980). According to Abt & Morrell (1995) the rotation of normal A stars must be slowed down by at least a factor of four before spectral peculiarities can develop. Moreover, the conclusion was made that the stellar rotational velocity is the only parameter that determines whether a star will have a normal or peculiar spectrum.

It is generally assumed that Ap stars are slow rotators because of magnetic braking. Whether they undergo deceleration after arrival on the main sequence (MS) or during the pre-MS phase has been discussed in a number of studies. Hartoog (1977) studied the Upper Scorpius region and a number of open clusters, and found no evidence for braking. Therefore he argued that most of the angular momentum is lost in the pre-main-sequence phase. North (1984) studied silicon stars belonging to clusters and associations as well as to the field. He showed that those stars lose most of their angular momentum before the main-sequence phase, or are intrinsically slow rotators from their formation on. He also found no hint of magnetic braking on the MS from a study of the distribution of the rotation periods as a function of the gravity (North 1985), and this has been confirmed recently on the basis of new surface gravities obtained from the Hipparcos data (North 1998a,b).

Recently, we have studied the evolutionary state of magnetic Ap stars of mass below $3M_{\odot}$ using Hipparcos data (ESA 1997). We could show that the distribution of Ap stars in the H-R diagram differs from that of the normal stars in the same temperature range at a high level of significance (Hubrig et al. 2000). The normal A stars occupy the whole width of the MS, without gap, whereas magnetic stars are concentrated towards the centre of the main-sequence band. In particular, it was found that magnetic fields appear only in stars that have already completed at least approximately 30% of their main-sequence lifetime. A few Ap stars with no or very weak magnetic fields for which good Hipparcos parallaxes are available show the same distribution in the H-R diagram as that of the strongly magnetic stars. The comparison of rotational periods of Ap stars of different ages in our sample did not present any evidence supporting the hypothesis that Ap stars suffer considerable magnetic braking during their MS life.

According to these results, there must exist progenitors of Ap stars in the form of normal A stars, which probably rotate slowly unless some unknown mechanism is able to brake their rotation in a very short time (say in 10^7 years or so) followed shortly by the appearance of the Ap characteristics. The existence of such slowly rotating progenitors would raise the question of why chemical peculiarities have not yet developed in them, since slow rotation is thought to favour their appearance. At the same time the question of the magnetic field is brought up: if it is already present in these progenitors, then there is no reason why they should remain normal rather than Ap, because the presence of a large-scale magnetic field stabilizes the stellar envelope so efficiently that the chemical peculiarities should appear in less than 10^6 years (Michaud et al. 1976). If it is not, why then would these progenitors rotate slowly? The reason for slow rotation seems indeed related with the presence of a strong magnetic field in the pre-MS phase (Stepien 2000). The

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existence of slowly rotating normal progenitors of magnetic Ap stars would only be possible, so it seems, when the magnetic field which was responsible for braking the pre-MS star rotation is buried under the surface of the star – allowing it to rotate slowly while staying chemically normal – and appears at the surface again after the star has completed 30% or more of its life on the MS. Young Am stars might fulfill these conditions: some are found in young clusters, including the Orion association (Smith 1972), and a few have slow rotation (Abt 1979). Large-scale magnetic fields are generally not found, either in normal A stars or in Am stars (Landstreet 1982), but some Am stars probably have more complicated fields (Lanz & Mathys 1993, Savanov 1995). However, many Am stars are evolved (Nicolet 1997), so that only part of the young Am stars might be considered as possible progenitors of magnetic Ap stars.

In the next section, we briefly examine what would be the necessary size of a sample of normal A stars with known rotational velocity, effective temperature and luminosity to provide a significant indication for the existence of slowly rotating progenitors of cool Ap stars. In the following sections, we examine a sample of 160 normal A stars with homogeneous $v \sin i$ determinations by Abt & Morrell (1995) and precise Hipparcos parallaxes, in order to see how rotational velocity changes with age.

2. The cost of looking for progenitors of Ap stars

According to Abt & Morrell (1995), there are 6.4% of Ap stars among all MS stars in the temperature range corresponding to the A type.

In view of such a low frequency, one immediately sees that it will be difficult to detect slowly rotating progenitors of Ap stars on the basis of a statistics of $v \sin i$ and luminosities of a sample of A stars. This is especially so because the distribution of equatorial velocities is very wide and is further widened by the uncertainty in $\sin i$.

Suppose we wish to detect a significant excess of slow rotators among young A stars (e.g. having completed less than 30% of their MS lifetime); we aim at a $3\,\sigma$ detection (significance better than 99%). Then, the minimum number N of young A stars would have to satisfy the equation

$$3\,\sqrt{N} = 0.064\,N \qquad (1)$$

assuming the frequency given by Abt & Morrell (1995) is realistic. The solution to this equation is $N \sim 2200$. The sample should then be almost 38 times larger than that of young, single and normal A stars with good Hipparcos parallaxes examined below. Such a large sample will only be available after a satellite such as GAIA will have expanded the sphere of stars with precise parallaxes, and also after some additional efforts in spectroscopic $v \sin i$ determinations. A quicker way may be to resort to photometric surface gravities, which can now be accurately calibrated using Hipparcos parallaxes.

In spite of the fact that a very large sample is required to test the existence of progenitors of Ap stars, we feel that before going straight to this question, it is worthwhile to see whether any significant difference appears between the $v \sin i$ distribution of young and old A stars in a much smaller sample. Indeed, before looking for subtle effects in a sample yet to be gathered, one has to understand the possible coarser ones. This is the purpose of the following sections.

3. Basic data

All in all, there are 416 bright ($V \leq 6.5$), single and normal A-type stars at distances below 100 pc ($\pi > 10$ mas) on the basis of their Hipparcos parallaxes, which are generally more precise than 10%. They are "normal" in the sense that all known Ap and Am stars have been excluded. In addition, they are single in the sense that all known spectroscopic binaries in the Bright Star Catalogue (Hoffleit & Jaschek 1982) have been discarded, as well as those having a variable radial velocity. To find possible differences of rotational velocity characteristics between young and old normal A stars we have used exclusively observational data on rotation presented by Abt & Morrell (1995). Of the 416 bright single A-type stars with accurate Hipparcos parallaxes, 160 stars have been measured by these authors.

The luminosity of the stars has been obtained by taking into account the standard bolometric correction of Schmidt-Kaler (1982). In addition, a version of the Lutz-Kelker (hereafter LK) correction (Lutz & Kelker 1973) modified to take into account a stellar density varying as a function of the distance from the galactic plane was applied.

The effective temperatures of the sample stars have been determined from photometric data, preferably in the Strömgren system, applying the calibration of Moon & Dworetsky (1985), or in the Geneva system (Hauck & North 1993; Hauck & Künzli 1996; Künzli et al. 1997).

The masses of the stars in our sample range from $2.5 M_{\odot}$ to $1.7 M_{\odot}$. They were obtained by interpolation in the theoretical evolutionary tracks of Schaller et al. (1992). The elapsed fraction of main-sequence life was interpolated from the same evolutionary tracks. Of the 160 stars in our sample, 102 have completed more than 30% of their main-sequence life.

4. Analysis

4.1. Distributions of $v \sin i$ for young and old stars

As a first step in comparing the observed rotational velocity distributions between young and old stars we have plotted the probability density versus $v \sin i$ distributions. Both distributions presented in Fig. 1 are very similar in that they show a maximum near $100\,\mathrm{km\,s^{-1}}$. There is no important excess of slow rotators in the distribution of the young A stars relative to that of the old stars; though, if one considers only stars with $v \sin i < 200\,\mathrm{km\,s^{-1}}$, the maximum of the distribution of young stars is slightly displaced towards lower $v \sin i$ relative to the distribution of old stars. A Kolmogorov-Smirnov test applied between both distributions confirms that they are not significantly different. The probability that both samples have different rotational velocity distributions is only 55.5% (Fig. 2). The same result is obtained when the samples are selected on

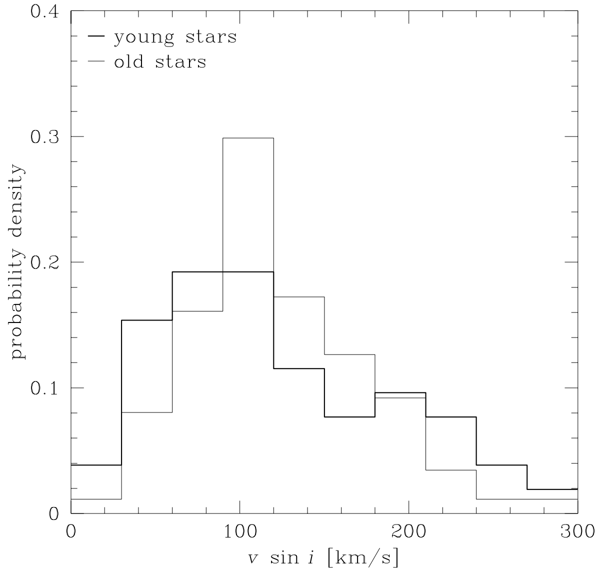

Fig. 1. Probability density vs. $v \sin i$ for 58 young (thick line) and 102 old (thin line) A stars

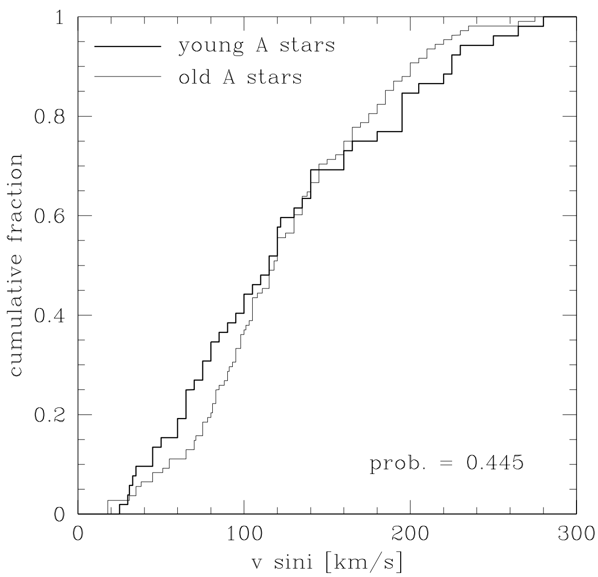

Fig. 2. Cumulative distribution of $v \sin i$ for the young A stars (thick line) and for the old A stars (thin line)

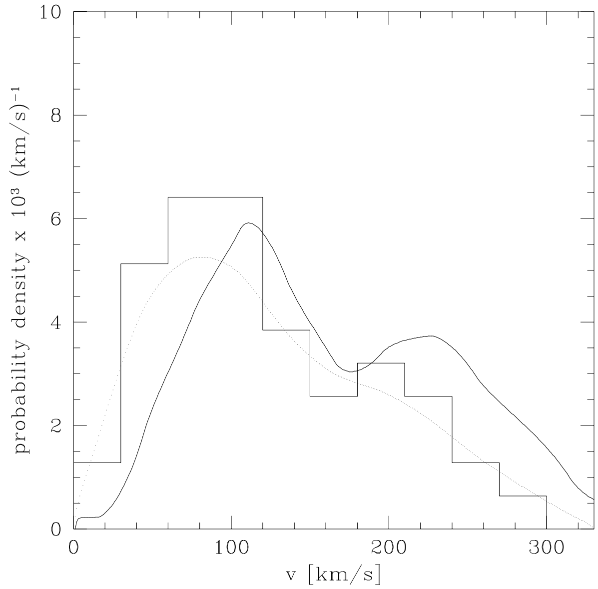

Fig. 3. Distribution of rotational velocities for 58 young A stars. The histogram represents the observed distribution of $v \sin i$ values; the solid line represents the distribution of the true rotational velocities $\psi(v)$ calculated on the assumption that the axes of rotation for the stars are randomly oriented and the dotted line represents the distribution of apparent rotational velocities $\phi(v \sin i)$ derived from $\psi(v)$.

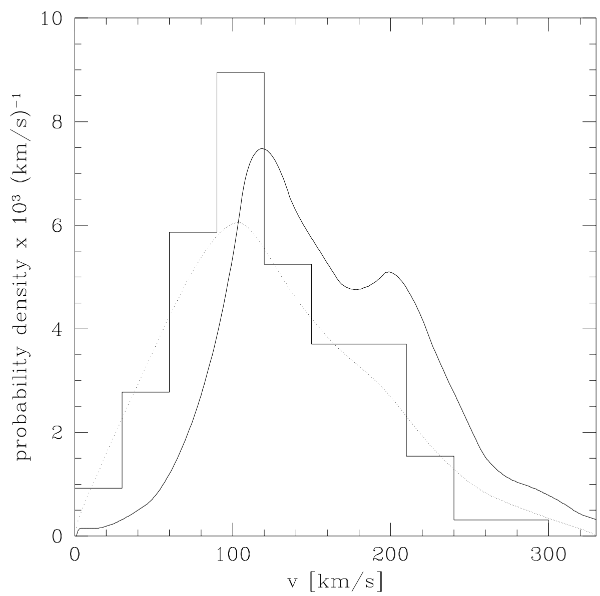

Fig. 4. Distribution of rotational velocities for 102 old A stars. The histogram represents the observed distribution of $v \sin i$ values; the solid line represents the distribution of the true rotational velocities $\psi(v)$ calculated on the assumption that the axes of rotation for the stars are randomly oriented and the dotted line represents the distribution of apparent rotational velocities $\phi(v \sin i)$ derived from $\psi(v)$.

the basis of $\log g$: the distributions of stars with $\log g < 3.9$, $3.9 \leq \log g \leq 4.1$ and $\log g > 4.1$ are statistically identical.

On the assumption that the axes of rotation for the stars in both samples are randomly oriented, it is possible to derive the distribution of true rotational velocities $\psi(v)$ from the observed distribution of apparent rotational velocities $\phi(v \sin i)$. In order to rectify the observed distribution for aspect effect we have used the iterative technique developed by Lucy (1974) which has the advantage that no assumption needs to be made about the form of $\psi(v)$. The results for both samples after three iterations are presented in Fig. 3 and Fig. 4. Additional iterations would increase the fine structure in $\psi(v)$ so that calculated $\phi(v \sin i)$ would follow in detail the observed histogram. However, due to our limited sample size, no significance can be attached to the small-scale structure, including in particular the minimum for $160 < v \sin i < 200\,\mathrm{km\,s^{-1}}$. Both distributions appear almost identical. The distribution $\psi(v)$ for the young A stars reaches

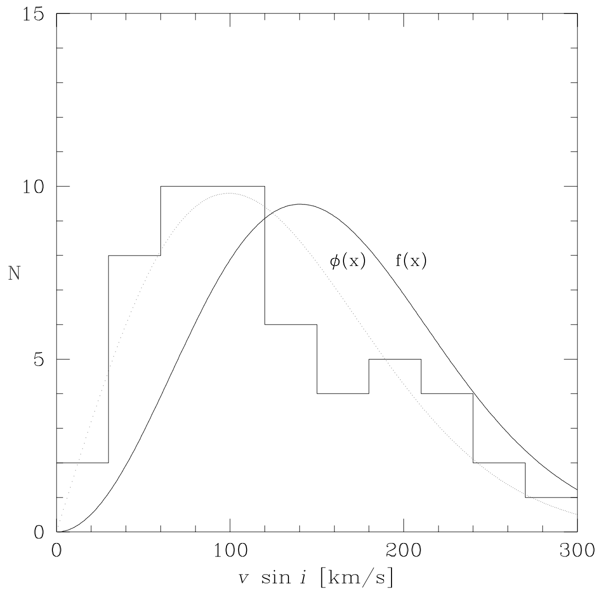

Fig. 5. Distribution of $v \sin i$ for the young A stars. The solid line represents the Maxwellian distribution of the true rotational velocities, $f(x)$. The dotted line represents the Maxwellian distribution of the observed rotational velocities, $\phi(x)$.

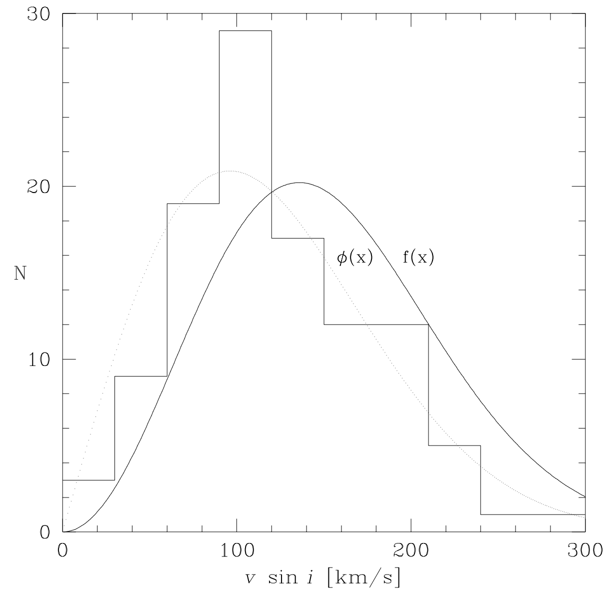

Fig. 6. Distribution of $v \sin i$ for the old A stars. The solid line represents the Maxwellian distribution of the true rotational velocities, $f(x)$. The dotted line represents the Maxwellian distribution of the observed rotational velocities, $\phi(x)$.

a maximum at about v=110 km s^{-1} and that for the old A stars reaches a maximum at about v=120 km s^{-1}. We obtain for the group of the young stars $\langle v \rangle = 160$ km s^{-1} and for the group of the old stars $\langle v \rangle = 161$ km s^{-1}.

Finally, we have tested the Maxwellian law for the representation of stellar rotation of the young and old stars. The Maxwellian distribution for the rotational velocities is expected on the basis of statistical mechanics arguments. Deutsch (1967; 1970) and Dworetsky (1974) have shown that a Maxwellian distribution that fits the distribution of rotational velocities of A stars predicts far fewer slowly rotating stars than actually found. In all previous studies all samples of stars were restricted to certain MK spectral types. Since no test has ever been done for the stars with a restriction on mass and age, it is obviously of great interest to use our samples to test the Maxwellian law.

As seen in Fig. 5, the distribution of rotational velocities of the young A stars can be represented fairly well by the Maxwellian law ($\chi^2 = 3.17, \mathrm{P} = 0.96$) with $\langle (v \sin i)^2 \rangle^{1/2} = 140$ km s^{-1}. A χ^2 test for the group of old stars indicates that the distribution of rotational velocities is non-Maxwellian ($\chi^2 = 8.85, \mathrm{P} = 0.45$) with $\langle (v \sin i)^2 \rangle^{1/2} = 136$ km s^{-1}. Most contribution to χ^2 arises from the excess number of stars with 90 km s^{-1} $< v \sin i <$ 120 km s^{-1} (Fig. 6).

4.2. Conservation of angular momentum

In order to interpret the data we consider what are the theoretical expectations about the evolution of equatorial velocity on the MS under some very simple assumptions.

Assuming there is no loss of any angular momentum, there are two extreme cases:

1. Conservation of angular momentum in spherical concentric shells of infinitesimal width, which are supposed to glide on top of each other without friction. There is no radial exchange of angular momentum, so only the external shell has to be considered in comparisons with observations. The moment of inertia relevant to the problem is that of a hollow sphere, so it increases during MS evolution with the square of the radius.
2. Complete radial exchange of angular momentum, i.e. rigid-body rotation. Here the relevant moment of inertia is that of the whole star: it must be computed by taking the whole internal structure of the star into account at each evolutionary stage. Since the core contracts, it increases less rapidly with evolution than in the first case.

In both cases, the equatorial velocity as a function of time follows this law:

$$V_{eq} = V_{eq_0}(R/R_0)(I_0/I) \quad (2)$$

where I is the moment of inertia (the subscript 0 refers to $t = 0$, i.e. the arrival of the star on the ZAMS) and $I/I_0 \propto (R/R_0)^2$ in the first case, but must be computed numerically in the second case.

The above equation may be written in a form better suited to observed quantities by introducing the surface gravity (the stellar mass is assumed constant, which is completely reasonable for the mass range considered):

$$\log(V_{eq}) = \log(V_{eq_0}) - 0.5 \cdot (\log g - \log g_0) - (\log I - \log I_0) \quad (3)$$

Fig. 7 shows the logarithmic run of $v \sin i$ against $\log g$ for the three masses 1.7, 2.0 and 2.5 $M_\odot$ according to the models of

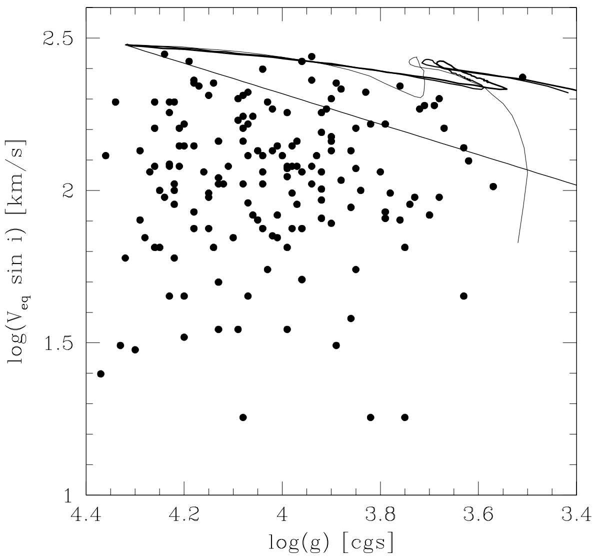

Fig. 7. Equatorial rotational velocity versus surface gravity. The scatter of the observed points is due both to the distribution of initial rotational velocities and to the projection ($\sin i$) effect. The three increasingly heavy curves are the evolutionary tracks for stars of 1.7, 2.0 and 2.5 $M_\odot$ respectively, in the case of rigid-body rotation. The thinner curve is for a 1.7 $M_\odot$ star, which leaves the MS at a larger $\log g$ value than more massive stars. The straight line represents the ideal case of no radial exchange of angular momentum.

Schaller et al. (1992), for the case of rigid-body rotation[1]. The extreme case of conservation of angular momentum in independent concentric shells appears as a straight line in this figure. In both cases, an initial equatorial velocity of 300 km s^{-1} was assumed.

It is clear that the rigid-body rotation appears to fit well the observations, although the latter are not very constraining since only their upper envelope can be used. On the other hand, the extreme case of conservation of angular momentum in independent shells appears completely unrealistic.

5. Conclusions

Present-day data are far from sufficient to prove the possible existence of progenitors of magnetic Ap stars among normal A stars. One should also recall here, that magnetic field measurements of normal A stars have always failed to yield significant values, though the sample measured remains small as yet (Landstreet 1982 measured 36 stars).

We found no statistically significant difference between the $v \sin i$ distributions of young and old A stars in the mass range 1.7 to 2.5 $M_\odot$. However, a very slight excess of slow rotators might be present among the young A stars, contrary to what would be expected from mere conservation of angular momentum.

The distributions of equatorial velocities have been obtained from those of the projected rotational velocities, and they do not differ significantly from the Maxwellian distribution in the case of the young stars. The distribution of the old stars differs marginally from the Maxwellian one, essentially because of an excess of moderate rotators ($v \sin i \sim 100\,\mathrm{km\,s^{-1}}$). Contrary to the results obtained by Deutsch (1967) and Dworetsky (1974), we do not find any excess of slow rotators.

Finally, the upper envelope of the observed points in the diagram $\log(v \sin i)$ vs. $\log g$ is very well represented by evolutionary tracks computed with the assumption of rigid-body rotation and conservation of angular momentum throughout the whole MS lifetime, while conservation of angular momentum in independent spherical shells is definitely ruled out.

[1] The thinner line, which represents a 1.7 $M_\odot$ star, seems to be different from the other ones. This is only due to the fact that 1.7 $M_\odot$ stars leave the MS with a larger surface gravity than more massive stars; similarly, they cross the Herzsprung gap at larger surface gravities: the evolutionary tracks for 2.0 and 2.5 $M_\odot$ show the same vertical drop as for 1.7 $M_\odot$, but around $\log g$ values of 3.32 and 3.03 respectively, i.e. beyond the limits of the diagram.

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