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The Angular Momentum Evolution in M67

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Abstract.
On the basis of accurate projected rotational velocity $v \sin\ i$ for 28 main sequence, turnoff and giant stars, we study the evolution of the angular momentum in old open cluster M 67. From these data, we show that early main sequence G stars have rotational velocity two times larger the Sun, with a possible trend with $(B-V)$ color, in that redder colors correspond to lower $v \sin\ i$. The stars at the turnoff are the fastest rotators, with $v \sin\ i$ between 6.3 and 7.6 $\mathrm{km\,s^{-1}}$, while stars just above the turnoff are already significantly slower. Along the Red Giant Branch rotation decreases smoothly and for stars redder than $(B-V) \gtrsim 1$, only upper limits can be found, including 4 clump stars. Analyzing the angular momentum history of 1.2 $M_{\odot}$ stars with the help of theoretical evolutionary tracks, we see that these stars probably obey different angular momentum evolution laws on the main sequence and along the Red Giant Branch: while on the main sequence some extra braking is required, in addition to angular momentum conservation, along the Red Giant Branch the data are well represented by the $I\Omega = C$ law. Finally, comparing the rotational velocity of the M 67 turnoff stars with their main sequence progenitors in younger open clusters, we find that younger clusters show substantially higher rotation rates, indicating that 1.2 $M_{\odot}$ stars do experience main sequence braking.

1. Introduction

Stellar rotation is a relevant observable in stellar astrophysics: not only it is crucial for our understanding of stellar chromospheric and coronal activity (see e.g. Noyes et al. 1984, Pallavicini et al. 1981), but also because the evolution of stellar angular momentum has been advocated as the responsible mechanism to explain mixing and dilution observations which cannot be otherwise reproduced in the context of non rotating stellar evolutionary models (Charbonnel and Talon 1999, Deliyannis et al. 2000). In addition, the discovery of fast rotating Horizontal Branch (HB) stars in globular clusters may have deep impact on our understanding of stellar interior structure (Peterson 1985). We can also expect that, once fully consistent rotating models are developed, they will have

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to satisfy not only the Color-Magnitude ($C-M$) diagrams and the abundance patterns observed, but also the observed evolution of the stellar angular momentum. On the other hand rotation in late type stars is a quantity which, despite its relevance, has often been neglected. The main reason is that old cool stars, either on the main sequence or evolved, tend to rotate very slowly and the direct measurement of $v \sin i$ is therefore a difficult task, which either requires very high resolution, high S/N observations (e.g. Gray 1976) or long term campaigns to determine rotational periods thanks to the modulation in the core of chromospheric lines induced by the migration of surface inhomogeneities on the stellar surface (see e.g. Baliunas & Vaughan 1985). Nevertheless, with the new generation of spectrometers like CORAVEL, CORALIE and FEROS, for example, it is possible to determine rotational velocities with a precision of about 1.0 km s^{-1}. In the present study we use rotational velocity $v \sin i$ obtained from FEROS observations to study the evolution of the angular momentum of 1.2 $M_{\odot}$ stars belonging to the old open cluster M 67.

2. Results

The rotational velocity $v \sin i$ were obtained by Melo et al. (2001) with the FEROS spectrometer (Kaufer et al. 1999) for 28 main sequence, turnoff and giant star belonging to the old open cluster M 67 (Montgomery et al. 1993). Let us recall that the uncertainty for these $v \sin i$ is better than 1.3 km s^{-1}.

In Figure 1 the color magnitude diagram of the observed stars is shown. The stars are sampled from the main sequence, to the turn-off and the RGB; in addition 5 clump giants are easily identified at $(B-V) \sim 1.1$ and $m_v \sim 10.6$.

In this figure the symbols are proportional to the measured $v \sin i$, and this crude representation already shows quite regular patterns associated with different regions of the $C-M$ diagram. In the same figure the evolutionary track for 1.2 $M_{\odot}$, solar metallicity is shown. The track is from Girardi et al. 2000), who kindly computed the stellar momentum of inertia for each step (see Pasquini et al. 2000). The track represents very well the turnoff region and the subgiants, while it is slightly redder than the observed stars along the RGB.

In Figure 2, $v \sin i$ as a function of the $(B-V)_0$ color is shown. The $v \sin i$ data have been corrected by $4/\pi$ to consider the projection effect.

In short, we can summarize the results of this study on the $v \sin i$ evolution of 1.2$M_{\odot}$ stars in M 67 as follow:

1. The stars behave in a very regular way as far as $v \sin i$ is concerned: at each position in the $C-M$ diagram they show similar values of $v \sin i$ (but more stars would help in investigating this point further).

2. Main sequence early G stars (Group 1) have rotational velocity between 4.3 and 5.8 km s^{-1}. There are indications that rotational velocity decreases with increasing $(B-V)$.

3. Turnoff stars (Group 2) show the highest values of rotational velocity, but a large drop is present as soon as the star evolves out of the turnoff (Group 3).

4. The rotational velocity continues to drop along the subgiant branch (Group 4), by a factor $\sim$ 2. Only upper limits could be obtained for stars with $(B-V) \gtrsim 1$ and this is also true for the clump stars.

To better quantify the evolution of the stellar angular momentum for stars in M 67, we used moment of inertia I as computed from the Girardi et al. (2000) tracks. We have then assumed simple functional laws for angular momentum evolution of the type $I\Omega^{\alpha} = C$ where C is a constant and α=0.5,1, 2 and we scale them to match the rotational velocity of the turnoff stars of M67. Note that this means that $V \sin i \propto R \times I^{-\frac{1}{\alpha}}$. R and I are taken from the evolutionary tracks. These simple laws assume solid body rotation; when $\alpha = 1$ this implies that the angular momentum remain constant along the evolution; $\alpha > 1$ implies that transfer of momentum from the interior, while $\alpha < 1$ requires some extra mechanism which tends to brake the rotation beyond what expected from angular momentum conservation. At the moment these curves can only give semi-quantitative answers, in that, as is clear from Figure 1 the evolutionary track does not reproduce perfectly the RGB of M67; this implies that the theoretical and observed I and radii may not be in perfect agreement on the RGB.

We nevertheless believe that the curves in Figure 2 are very interesting: they show that the subgiant and RGB parts of the observations are well represented by a $I\Omega = C$ law; this implies that other effects influencing the angular momentum evolution, such as internal redistribution or magnetic braking, if present at all, should be not very relevant for these stars. On the other hand, it is clear that the region of the turnoff cannot be reproduced by such a law: for $I\Omega = C$ the decrease of rotation predicted between the phases around the turnoff hook is negligible, at odds with the observations. A much steeper law, such as $I\Omega^{0.5} = C$ is required, but this would slow down too much the stars along the subgiant branch.

Finally, a comparison of the observations with simple angular momentum laws as derived from theoretical models shows that, while along the RGB M 67 stars evolve close to an angular momentum conservation law $I\Omega = C$, at the tip of the turnoff a stronger braking is required to match the observations. The fact that these stars are suffering MS braking is interesting also in connection with the fact that they belong to the "Lithium dip", a feature which still lacks a firm explanation, and for which angular momentum history has often been invoked as a cause (Deliyannis et al. 1997, Charbonnel & Talon 1999).

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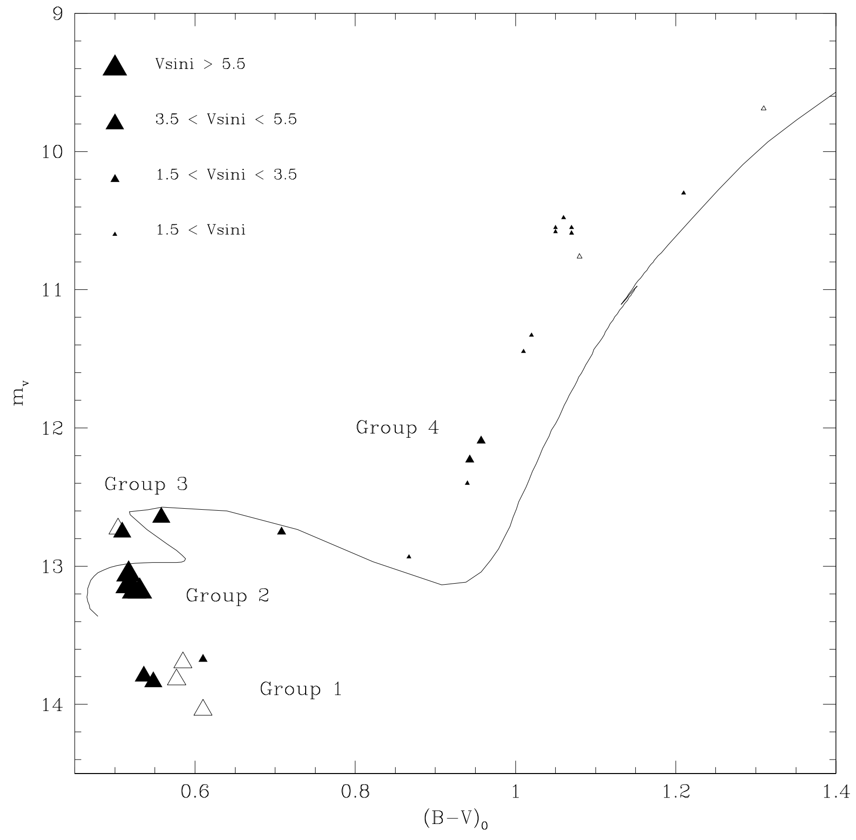

Figure 1. The color magnitude diagram of the observed stars in M 67 is shown. Singles stars are shown as filled triangles, while binaries are represented by empty triangles. Symbols size is proportional to the observed $v \sin\, i$. Correction for $E(B-V) = 0.05$ has been applied. Overimposed is the 1.2 $M_{\odot}$ evolutionary track from Girardi et al. (2000) used to compute the stellar momentum of inertia.

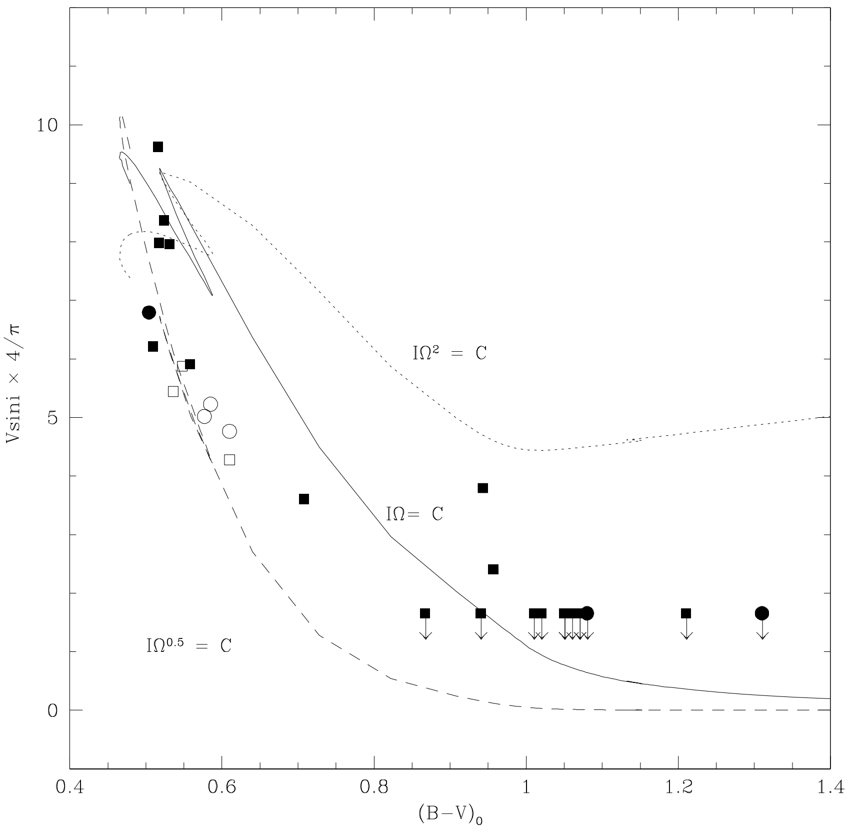

Figure 2. Rotational velocities vs. $(B-V)_0$ color for the M 67 stars. Open squares (circles) show main sequence single (binary) stars. Filled squares (circles) represent turnoff and evolved single (binary) stars. The different curves represent simple hypothesis on the evolution of angular momentum: $I\Omega = C$ (Continuous line), $I\Omega^2 = C$ (dotted) and $I\Omega^{0.5} = C$ (dashed).