Young Cool Stars Divided on the Issue of Rotation

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Abstract.
We present the results of a combination of new stellar rotation periods and extensive information about membership in the young open clusters M 35 and M 34. The observations show that late-type members of both M 35 and M 34 divide into two distinct groups, each with a different dependence of rotation on mass (color). We discuss these new results in the context of existing rotation data for cool stars in older clusters, with a focus on the dependence of rotation on mass and age. We mention briefly tests of rotation as an “astronomical clock” (gyrochronology), and our plans to use the Kepler space mission to push observations of stellar rotation periods beyond the age of the Hyades and the Sun.

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INTRODUCTION

Understanding the evolution of stellar rotation is an integral part of understanding stellar evolution. Clusters of stars allow us to probe their rotational evolution as a function of their most fundamental properties - mass and age. For cool stars (here: 0.5 \textlesssim} M_\odot < 1.25) in young open clusters, rotational periods can be measured to very high precision. Combined with cluster membership information, such observations now reveal clear relations between stellar rotation, age, and mass.

Early observations of cool stars in open clusters younger than the Hyades discovered that they rotate with periods ranging over two orders of magnitude - from near breakup to periods similar to the Sun [see e.g. 1, 2, 3, and references therein]. This early information was primarily from spectroscopic observations giving projected rotational velocities ($v \sin i$), affected by the sin $i$ ambiguity and the need to determine the stellar radius to derive the angular rotation velocity. Despite these ambiguities, some structure in the distribution of $v \sin i$ with stellar color was noted, as was an emerging time- and mass-dependence for the presence of ultra fast rotators (UFR). UFR were primarily found among the K and M dwarfs in \alpha Persei and the Pleiades, while lacking altogether in the older Hyades cluster. These observations prompted ideas about the processes in cool stars responsible for their rotational evolution, such as the suggestion of epochs of decoupling and recoupling of the stellar core and envelope [4, 3].

Recently, from a study of rotational period data for several young open clusters, Barnes (2003) [5, hereinafter B03] proposed that stars fall along two “rotational sequences” in the color vs. period plane. From an analysis of these sequences and their dependencies on stellar age, B03 proposed a framework for connecting internal and ex-
ternal magneto-hydrodynamic processes to explain the evolution in the observed period distributions. This approach combines the ideas of initial decoupling of the stellar core and envelope, with re-connection of the two zones through a global dynamo-field at a later and mass-dependent time. B03 also proposed that the evolution of the rotational sequences in the color-period diagram, could be used to measure the age of a stellar population, much like the sequences in the color-magnitude diagram. A similar idea had been proposed by Kawaler [6]. Barnes [7] further developed this idea of “gyrochronology”.

Interpretation aside, it is desirable and increasingly possible to eliminate the ambiguities of $v \sin i$ data by measuring rotational periods from light modulation by star-spots. It has also become more feasible to carry out comprehensive surveys for kinematic membership in star clusters. Combining the two reveals new details about dependencies of rotation on the most fundamental stellar properties - mass and age.

NEW OBSERVATIONS OF TWO YOUNG CLUSTERS

We carried out photometric monitoring campaigns over 5 consecutive months for rotational periods, and nearly decade-long radial-velocity surveys for cluster membership and binarity, on the 150 Myr and 200 Myr open clusters M 35 and M 34. For full descriptions of the observations, data-reduction, and data-analysis, see Meibom and Mathieu [9], Meibom et al. [10, 8], and Braden et al. [11].

Time-Series Photometric Observations: We surveyed, over a timespan of 143 days, a region of $40 \times 40$ arc minutes centered on each cluster. Images were acquired at a frequency of once a night both before and after a central block of 16 full nights with

FIGURE 1. The distribution of stellar rotation periods with (B-V) color index for 310 members of M 35 (left; [8]) and 79 members of M 34 (right). Dark blue plotting symbols are used for radial-velocity members and light blue for photometric members.
observations at a frequency of once per hour. The data were obtained in the Johnson V band with the WIYN 0.9m telescope on Kitt Peak. Instrumental magnitudes were determined from Point Spread Function photometry. Light curves were produced for more than 14,000 stars with $12 < V < 19.5$. Rotational periods were determined for 441 and 120 stars in the fields of M 35 and M 34, respectively (see Figure 1).

The spectroscopic surveys: M 35 and M 34 have been included in the WIYN Open Cluster Study (WOCS; Mathieu [12]) since 1997 and 2001. As part of WOCS, 1-3 radial-velocity measurements per year were obtained on both clusters within the 1-degree field of the WIYN 3.5m telescope with the multi-object fiber positioner (Hydra) feeding a bench mounted echelle spectrograph. Observations were done at central wavelengths of 5130Å or 6385Å with a wavelength range of $\sim 200$Å. From this spectral region with many narrow absorption lines, radial velocities were determined with a precision of $< 0.4$ km/s [13, 14]. Of the stars with measured rotational periods in M 35 and M 34, 203 and 56, respectively, are radial-velocity members of the clusters (dark blue symbols in Figure 1). Including photometric members (light blue symbols in Figure 1), the total number of stars with measured rotational periods in M 35 and M 34, are 310 and 79, respectively.

THE COLOR-PERIOD DIAGRAM

Figure 1 shows the rotational periods in M 35 and M 34 plotted against $B - V$ color. The coeval stars fall along two well-defined sequences representing two different rotational states. One sequence displays a clear correlation between period and color, and forms a diagonal band of stars whose periods are increasing with increasing color index (decreasing mass). The second sequence consists of UFR and shows little mass dependence. Finally, a small subset of stars is distributed between the two sequences. The distribution of stars in the color-period diagrams suggests that the rotational evolution is slow where we see the sequences, and fast in the gap between them, while other areas of the color-period plane are either unlikely or “forbidden”.

While much more apparent in M 35 and M 34, and in the study by Hartman et al. [15] of the 550 Myr cluster M37 (see below), the sequences seen in Figure 1 are the same as identified by B03. B03 named the diagonal sequence the interface (I) sequence, and the sequence of UFR the convective (C) sequence. Barnes argues that stars on the C sequence have decoupled radiative cores and convective envelopes, and suggests that the evolution of their surface rotation is governed primarily by the moment of inertia of the envelope and by inefficient loss of angular momentum linked to small-scale convective magnetic fields. For stars on the I sequence, B03 suggests that large-scale (sun-like) magnetic fields, produced by an interface dynamo, provide more efficient Skumanich-style angular momentum loss. B03 suggests that a late-type star evolves from the C sequence and onto the I sequence when rotational shear between the stellar core and envelope establish a large-scale dynamo field. This happens sooner in higher mass stars as they have thinner convective envelopes with smaller moments of inertia.
The evolving color-period diagram: timescales, and mass-dependence

Color-period diagrams for clusters of different ages allow us to study the rotation of cool stars as a function of mass and age. In Figure 2 (left) we show the color-period diagrams for M 35 (150 Myr), NGC 3532 (B03; 300 Myr), and M37 (550 Myr). This diagram reveals both stellar spin-down on the I sequence and a mass-dependence of the timescale for “migration” from the C to the I sequence. At 150 Myr (M 35) G dwarfs have evolved onto the I sequence, by 300 Myr (NGC 3532) the early K dwarfs have followed, and by 550 Myr (M 37) most of the late K dwarfs are on the I sequence as well. In Figure 2 (right), we add M 35 and M 34 to Fig. 3 in B03 which shows the fractions of cluster stars on the I and C sequences as a function of their ages. M 35 and M 34 fit well the evolutionary trends of a decreasing fraction of C sequence (and gap) stars and an increasing fraction of I sequence stars with age. The almost linear trends suggest an exponential change in time of the number of stars on the sequences. By counting stars on both sequences and in the gap in the M 35 color-period diagram, and making the assumption that all stars start on the C sequence at the ZAMS, we estimate the characteristic timescale for the rotational evolution of stars off the C sequence and onto the I sequence. We derive \( \tau_{c}^{G} = 60 \) Myr and \( \tau_{c}^{K} = 140 \) Myr for G and K dwarfs, respectively. Such timescales may offer valuable constraints on the evolution of stellar dynamos and internal and external angular momentum transport.
FIGURE 3. The M 35 (left) and M 34 (right) color-period diagrams with 25 Hyades stars overplotted (red symbols). In both plots, the Hyades rotation periods were spun-up by factors of $\sqrt{625/150}$ and $\sqrt{625/200}$, respectively, in accordance with the Skumanich $\sqrt{t}$ time-dependence on stellar rotation evolution, and an age of 625 Myr for the Hyades [16].

Testing the Skumanich relationship ($P_{\text{rot}} \propto \sqrt{\text{age}}$)

On the I sequence, angular momentum loss ($dJ/dt$) is thought to be proportional to the angular rotation velocity ($\Omega$) to the third power ($dJ/dt \propto \Omega^3$). This relationship has been used in the most recent models of angular momentum evolution for late-type stars [e.g. 17, 18, 19, 20, 21]. Its origin is in magnetized stellar wind theory [22, and references therein]. However, assumptions were made about the geometry of the global magnetic field ($B$), and about the relation between $B$ and $\Omega$, in order to satisfy the Skumanich relationship ($P_{\text{rot}} \propto \sqrt{\text{age}}$). We note that the Skumanich relationship was derived based on $v\sin i$ data for solar-like stars (G dwarfs) in open clusters and for the Sun. We ask here if the Skumanich relationship is also valid for stars of lower mass?

Figure 3 shows color-period diagrams in which the M 35 and M 34 stars are plotted together with Hyades stars. The Hyades stars have been spun-up in accordance with the Skumanich $\sqrt{t}$ time-dependence. Comparing stars on the I sequence, the $\sqrt{t}$ dependence appears to represent well the rotational evolution of the G dwarfs between 150 Myr/200 Myr and 625 Myr, whereas the spun-up Hyades K-dwarfs have rotation periods systematically shorter than the M 35 and M 34 K dwarfs. This suggests that the time-dependence on spin-down of K dwarfs is slower than $\sqrt{t}$ in the age-interval studied. A more detailed study of deviations from the Skumanich relationship is underway.
Testing gyrochronology

The idea of using the relations between stellar rotation, color (mass), and age, to determine the latter from observations of the former two, was proposed by Kawaler [6] and B03 (gyrochronology). Each proposed an expression relating the age of a star to its rotation period and $B - V$ color. We show in Figure 4, the distributions of ages calculated using the expression in B03 for I sequence stars in M 35 and M 34. The mean gyro-ages for M 35 and M 34 are 137 Myr and 188 Myr. The corresponding mean gyro-ages using the Kawaler [6] expression are 161 Myr and 217 Myr. Both sets of gyro-ages fall within the range of the isochrone ages determine for the two clusters (see Meibom et al. [8] for a more detailed comparison and discussion).

The Kepler mission - a unique opportunity

The Kepler space mission - a search for transiting earth-like planets - will provide time-series photometry of unprecedented duration, cadence, and precision. The location of 4 open clusters within the Kepler field of view, with ages from $\sim$0.5 Gyr till $\sim$8 Gyr, offers a unique opportunity to measure rotational periods for cool stars beyond the age of the Hyades and the Sun, and thereby extent the age-dimension of studies of stellar angular momentum evolution. The author is leading an effort to study the clusters with Kepler.
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