The Ages of Stars
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Stellar ages from stellar rotation

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Abstract. Our ability to determine stellar ages from measurements of stellar rotation, hinges on how well we can measure the dependence of rotation on age for stars of different masses. Rotation periods for stars in open clusters are essential to determine the relations between stellar age, rotation, and mass. Until recently, ambiguities in $v \sin i$ data and lack of cluster membership information, prevented a clear empirical definition of the dependence of rotation on color. Direct measurements of stellar rotation periods for members in young clusters have now revealed a well-defined period-color relation. We show new results for the open clusters M35 and M34. However, rotation periods based on ground-based observations are limited to young clusters. The Hyades represent the oldest coeval population of stars with measured rotation periods. Measurements of rotation periods for older stars are needed to properly constrain the dependence of stellar rotation on age. We present our plans to use the Kepler space telescope to measure rotation periods in clusters as old as and older than the Sun.

Keywords. stars: rotation, stars: evolution, Galaxy: open clusters and associations: general

1. Introduction

Knowing stellar ages is fundamental to understanding the time-evolution of various astronomical phenomena related to stars and their companions. Accordingly, over the past decades much work has been focused on identifying the properties of a star that best reveal its age. For coeval populations of stars in clusters, the most reliable ages are determined by fitting model isochrones to single cluster members in the color-magnitude diagram. However, for the vast majority of stars not in clusters (unevolved late-type field stars), ages determined using the isochrone method are highly uncertain because the primary age indicators are nearly constant throughout their main-sequence lifetimes, and because their distances and thus luminosities are poorly known. Therefore, finding a distance-independent property of individual stars that can act as a reliable determinant of their ages will be of great value.

Stellar rotation (and the related measure of chromospheric activity - see paper by Mamajek, this volume) has emerged as a promising and distance- independent indicator of age (e.g. Skumanich 1972; Kawaler 1989; Barnes 2003, 2007). Skumanich (1972) first established stellar rotation as an astronomical clock by relating the average projected rotation velocity in young open clusters to their ages via the expression $\overline{v \sin i} \propto t^{-0.5}$. The Skumanich relation is limited in mass (color) to early G dwarfs and suffers from the ambiguity (due to the unknown inclination angle) of the $v \sin i$ data. Furthermore, for ages beyond that of the Hyades cluster ($\sim$ 625Myr), the Skumanich relationship is constrained only by a single G2 dwarf - the Sun.

Modern photometric time-series surveys in young open clusters can provide precisely measured stellar rotation periods (free of the $\sin i$ ambiguity) for F, G, K, and M dwarfs. Based on such new data and emerging empirical relationships between stellar rotation, color, and age, a method was proposed by Barnes (2003) to derive ages for late-type dwarfs from observations of their colors and rotation periods alone. We refer the reader to the paper in this volume by Barnes for a motivation and description of the method of *gyrochronology*. However, our ability to determine stellar ages from stellar rotation, hinges on how well we can measure the dependence of rotation on age for stars of different masses.

2. The key role of open clusters

As coeval populations of stars with a range of masses and well determined ages, open cluster fulfill a critically important role in calibrating the relations between stellar age, rotation, and color. Indeed, *open clusters can define a surface in the 3-dimensional space of stellar rotation period, color, and age, from which the latter can be determined from measurements of the former two* (see Figure 2 below).

This inherent quality of open clusters can only be fully exploited if precise stellar rotation periods (free of the $\sin i$ ambiguity) are measured for cluster members. Accordingly, the time base-line and frequency of time-series photometric observations must be long enough and high enough, respectively, to avoid a bias against detecting periods of more slowly rotating stars, and to avoid detection of false rotation periods due to aliases and a strong "window-function" in the data. Furthermore, measured rotation periods should be combined with information about cluster membership and multiplicity. Removing non-members and stars in close binaries affected by tidal synchronization will allow a better definition of the relationship between rotation period and color at the age of the cluster. Finally, identification of single cluster members will enable a better cluster age to be determined from isochrone fitting. The new results for the open clusters M35 and M34 shown in Figure 1, reflect the powerful combination of decade-long time-series spectroscopy for cluster membership and time-series photometry over 5 months for stellar rotation periods.

3. New observations in the open clusters M35 and M34

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 M35 and M34. For detailed descriptions of the observations, data-reduction, and data-analysis, see Meibom and Mathieu (2005); Meibom *et al.* (2006, 2008), and Braden *et al.* (2009).

Time-Series Photometric Observations: We surveyed, over a timespan of 143 days, a region of 40×40 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 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 M35 and M34, respectively (see Figure 1).

The spectroscopic surveys: M35 and M34 have been included in the WIYN Open Cluster Study (WOCS; Mathieu (2000)) 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 ∼200Å . From this spectral region with many

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narrow absorption lines, radial velocities were determined with a precision of < 0.4 km/s (Geller *et al.* 2008; Meibom *et al.* 2001). Of the stars with measured rotational periods in M35 and M34, 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 M35 and M34, are 310 and 79.

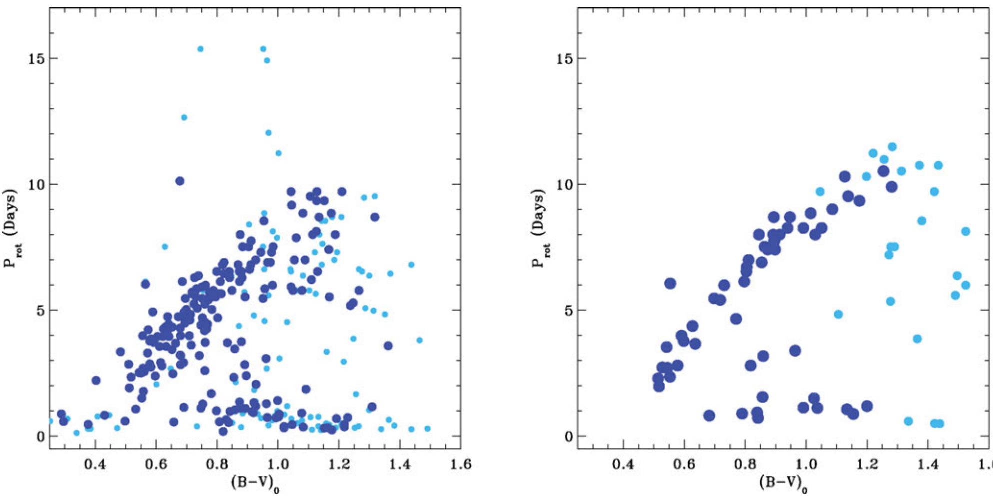

Figure 1. The distribution of stellar rotation periods with (B-V) color index for 310 members of M35 (*left*; (Meibom *et al.* 2008)) and 79 members of M34 (*right*). Dark blue (black) plotting symbols are used for radial-velocity members and light blue (grey) for photometric members.

4. The color-period diagram

Figure 1 shows the rotational periods for members in M35 and M34 plotted against their dereddened $B - V$ colors. The coeval stars fall along two well-defined sequences representing two different rotational states. One sequence displays a clear correlation between rotation 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 rapidly rotating stars and shows little mass dependence. 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. Other areas of the color-period plane are either unlikely or “forbidden”.

5. The dependence of stellar rotation period on color

For our purpose of determining the dependence of stellar rotation on stellar color, we can focus on the diagonal sequence of more slowly rotating stars in Figure 1. We can do so because surveys for stellar rotation in the older clusters M37 (550 Myr) and the Hyades (625 Myr) show that F, G, and K dwarfs spin down over a few hundred million years and converge onto this sequence (Hartman *et al.* 2008; Radick *et al.* 1987).

Barnes (2003, 2007, and this volume) refer to the diagonal sequence as the Interface (I) sequence and propose a 2 parameter function ($f(B-V)$) to represent it (Barnes 2007):

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$$P(t, B-V) = g(t) \times f(B-V) \tag{5.1}$$

where

$$f(B-V) = a((B-V) - b)^c \tag{5.2}$$

with $a = 0.77$ and $c = 0.60$. Barnes (2007) fix b at a value of 0.4, and determine $g(t) = t^{0.52}$.

From the method of gyrochronology (Barnes 2003, 2007), the functional dependence between stellar color and rotation period ($f(B-V)$) will directly affect the derived ages, and will, if not accurately determined, introduce a systematic error. It is therefore important to constrain and test the color-rotation relation for stars on the I sequence as new data of sufficiently high quality becomes available. Meibom *et al.* (2008) fit $f(B-V)$ as given in equation [5.2] to the I sequence stars in M35, leaving all 3 coefficients (a, b, c) as free parameters. They get the same value of 0.77 for a, but a slightly different value of 0.55 for c. By leaving the translational term b free, a value of 0.47 was found. This value for b is interesting because it corresponds to the approximate $B-V$ color for F-type stars at the transition from a radiative to a convective envelope. This transition is also associated with the onset of effective magnetic wind breaking (e.g. Schatzman 1962), and known as the break in the Kraft curve (Kraft 1967). The value of 0.47 for the b coefficient therefore suggest that, for M35, the blue (high-mass) end of the I sequence begins at the break in the Kraft curve.

The I sequence in M34 is particularly well-defined and will be used to further constrain the dependence between rotation and color in a forthcoming paper (Meibom *et al.*, in preparation).

6. The dependence of stellar rotation on age

With well-defined color-rotation relations (I sequences) for clusters of different ages, we are able to constrain the dependence of stellar rotation on age for stars of different masses. Comparison of the rotation periods for F-, G-, and K-type I sequence dwarfs at different ages enable a direct test of the Skumanich relationship for early G dwarfs and for dwarfs of higher and lower masses.

Initial comparisons in Meibom *et al.* (2008) between the rotation periods of G and K dwarfs on the I sequences in M35 and the Hyades, suggest that the Skumanich time-dependence ($P_{rot} \propto t^{0.5}$) can account for the evolution in rotation periods between M35 and the Hyades for G dwarfs. However, the time-dependence for spin-down of K dwarfs is different and slower than Skumanich. In a more in depth analysis (preliminary results) Meibom *et al.* (2009; in preparation), calculate the mean rotation periods for late-F, G, early K, and late-K I sequence dwarfs in M35, M34, NGC3532 (Barnes 2003; 300 Myr), M37, and the Hyades. They find that the increase in the mean rotation period with age is consistent with Skumanich spin-down for the late-F and G dwarfs, whereas K dwarfs spin down significantly slower. The deviations from the Skumanich spin-down for K dwarfs, suggest that the rotation period for late-type stars cannot be expressed as the product of separable functions of time and color (Eq. [5.1]). Skumanich spin-down was assumed for late-F through early M stars in Barnes (2003, 2007) and in Kawaler (1989).

Eventually, when rotation periods of sufficient quality is available for a larger number of clusters, the effects on the rotational evolution of other stellar parameters, e.g. metallicity, and of the cluster environment, should be considered. Irwin, this volume, give a more complete list of published rotation data in clusters.

7. The Kepler mission - a unique opportunity

At the present time, the Hyades represent the oldest coeval population of stars with measured rotation periods. Measurements of rotation periods for older late-type dwarfs is needed to properly constrain the dependence of stellar rotation on age and mass and to calibrate the technique of gyrochronology. Figure 2 shows a schematic of the surface in the 3-dimensional space of rotation, color, and age. At the present time this surface is defined solely by color-period data in young clusters and for the Sun. The solid black curves represent the ages and color-ranges of FGK dwarfs in M35, M34, NGC3532, M37, and the Hyades. The color and age of the Sun is marked as a solid dot. The figure demonstrates clearly the need for observations of stellar rotation periods beyond the age of the Hyades.

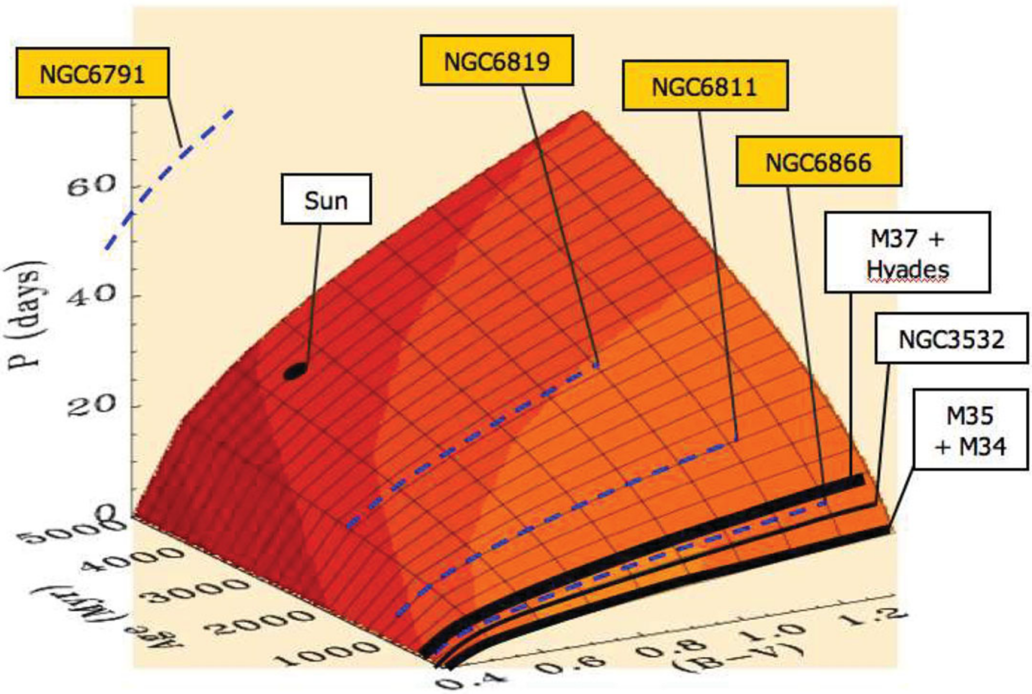

Figure 2. A schematic of the (presumed) empirical surface in the 3-dimensional parameter space of stellar age (Myr), color, and rotation period. The surface is currently defined *only* by stars in young open clusters (black solid lines), and by the Sun (black dot). The dashed blue lines mark the ages and approximate color ranges of FGK dwarfs in the 4 open clusters within the Kepler field.

The lack of periods for older stars (with the exception of the Sun) reflects the challenging task of measuring - from the ground - photometric variability for slowly rotating stars with ages of ∼1Gyr or more. However, the Kepler space telescope (scheduled for a 2009 launch), will provide photometric measurements with a precision, cadence, and duration, sufficient to measure stellar rotation periods from brightness modulations for stars as old as and older than the Sun. Four open clusters are located within the Kepler target region: NGC 6866 (∼0.5 Gyr), NGC 6811 (∼1 Gyr), NGC 6819 (∼2.5 Gyr), and NGC 6791 (∼10 Gyr). With Kepler we therefore have a unique opportunity to extend the age-rotation-color relationships beyond the age of the Hyades and the Sun. The dashed blue curves in Figure 2 mark the ages and approximate color ranges of FGK dwarfs in the 4 clusters.

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