Rotation Periods and Relative Ages of Solar-Type Stars

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The relationship between stellar rotation periods ($P_{\text{rot}}$) and relative ages of stars in a sample of Sun-like stars was examined, then compared to other age determination methods. The majority of stars exhibited increasing $P_{\text{rot}}$ as a function of increasing age, as expected. The accuracy of the analysis was confirmed when the stars reflected the characteristics of the Vaughan-Preston gap, which was discovered in 1983. However, the discovery of significant anomalies gave several implications. First, data collection methods at Mount Wilson Observatory need to be refined; quality and quantity of observations need to be increased. Second, up to a third of the stars could be in their Maunder Minimum activity minimums, which occur on centuries-long timescales and occupy one-third of the lifetime of a star. This fact gives a possible error of up to 33.3%. Another source of error is the possibility of active region growth and decay, which produces abnormally high rates of rotation. Third and final, the model for predicting age based on rotation period of a star should not depend on its spectral type (or mass). Previous formulae utilized convective turnover time (a function of spectral type) as a coefficient in the algorithm to determine age; the first results of this study indicate that rotation periods and relative ages of solar-type stars are related, but independent of spectral type.

Introduction

Stellar age, rotation period ($P_{\text{rot}}$), and activity fluxes ($S$) are intimately linked in lower main sequence (LMS) stars such as the Sun (Radick et al. 1990). Comparing ages inferred from activity fluxes to those inferred from rotation periods will determine the validity of stars' estimated ages, as well as determine the validity of each of these age determination methods. This study presents first results of the increase in rotation period as a star matures on the lower main sequence. However, notable inconsistencies in plotted trends implicate that basing a formula for $P_{\text{rot}}$ on color index is questionable.

Currently, other projects in the stellar rotation field are being conducted. At the Von Vleck Observatory, the Orion Monitoring Update, started in 1990, is a program to measure the rotation periods of 700 stars with a 24-inch telescope. Seventy-five of the 700 stars measured exhibit a $P_{\text{rot}}$ with a False Alarm Probability (FAP) of less than 1%. The Spotted Stars III Project began in March of 1995 with the goal of investigating $P_{\text{rot}}$ of stars in clusters. The slow-rotating stars in $\alpha$ Per and the Pleiades are constantly examined for new periods. The NGC 6475 and IC4665 clusters are also being studied.

To accurately measure the ages of stars, the consistencies of the various age-determination methods must be gauged. Current methods include the examination of characteristics such as isochrones, chromospheric emissions, metallicities, and period of activity cycle $P_{\text{cyc}}$.
Julian calendar system. Magnetic heating occurs in the chromospheres of stars; starspots are greatest where magnetic fields are greatest. Hence, as starspots or inhomogeneities travel across the surface of a star, Ca II flux will reflect that movement (Donahue 1993). Ca II flux is thus used to observe rotation periods.

The search for rotational signals was performed on a set of 102 LMS stars taken from the MWO sample. Criteria for these stars’ selection included a B - V color index similar to that of the sun’s (i.e., 0.55 < B - V < 0.76). The number of experimental data points each star had varied from 50 to over 3000, due to the rolling inclusion of stars in the HK project. To begin the search, data points were organized into seasons, with a season defined as an interval containing at least 30 data points and separated from other intervals by at least 80 days.

Determining P_rot required various techniques. The primary means of obtaining P_rot was the use of the program “j,” created by R. A. Donahue in 1993. J plots activity-versus-time observations (activity = S is measured by monitoring the emission core fluxes within Ca II H and K resonance lines from LMS stars). An example of a time series plot of Ca II flux is shown in Figure 1A.

J performs Fourier transform periodograms of data points. J is specifically designed to handle data series with uneven rates of sampling (Horne and Baliunas 1986). A sample periodogram of star HD 82885 is shown in Figure 1B. At least one periodogram was computed for each observing season; filtering was necessary for transforms with second peaks. Gaps in the data were filled by executing j manually on selected time intervals.

Another function of j that was utilized is its output of False Alarm Probability (FAP) of periods detected. FAP—the chance in percent that a measured periodic peak will arise from purely random (Gaussian) noise—serves as an indicator of quality of period detection. It is desirable to look for FAPs close to zero when searching for a final rotation period. The stars were ranked on a negative log FAP scale, which was labeled as FApH because of the similarity to the pH scale.

Each star received at least five comprehensive reviews of its detected period. Observed periods of less than 5 days and greater than 100 days were generally not considered as candidates for designation of a rotation period. Rotation periods of less than five days could be spurious because measurements were made two to three days apart. Rotation periods longer than 100 days are beyond the seasonal window of the observations. When periods fell within a range of 10 days or less, the mean was calculated and the standard deviation utilized in place of δP_rot. A file summarizing detected P_rot, δP_rot, and FAP was created for each star.

**Results**

Of a total of 102 stars, only 46 had been observed with enough data to span one to three seasons. Six stars had only 3-10 points of data, and thus did not qualify for even a single season. However, fifty-one out of 102 stars exhibited a measurable P_rot. Thirty of these stars exhibited FAPs of less than 1.0 x 10^-3, which indicates a fairly accurate period.

Among the 51 stars with observable seasons, there were 29 (56.7%) with periods detected in one to three seasons. Eighty-two percent of these stars had detectable periods in at least 50% of their seasons. These statistics may be misleading when examined out of context. Half of the stars have only one or two observable seasons. Therefore, finding a period in one season inflates period percentages. However, the determined periods should be given considerable weight because they are relatively more consistent than their flat counterparts. Additionally, gaps in data and indeterminate rotation periods are common in the field of rotation study (Radick et al. 1990).

Thirty stars in the main sample did not receive a P_rot designation. Data for 26 of these stars were so sparse that a rating of “NMI,” or Need More Information, was given. Fourteen stars in the sample earned a rating of “NDP,” or No Detectable Period. This occurred when stars showed conflicting P_rot over various seasons, causing any P_rot obtained to be unreliable. Only nine stars were flat, meaning that they exhibited no discernible P_rot at all, and instead yielded static time series plots.

Sixteen stars were found to have equivocal rotation periods. These periods featured high False Alarm Probabilities, indicating they were not likely to be accurate.
Age versus Rotation. Several conclusions may be reached concerning the relationship between a star’s age and its rotation period. To begin, smaller intrinsic spread in $P_{\text{rot}}$ is characteristic of older LMS stars, but not young ones. This observation is apparent in Figures 3 and 4. The residuals of $P_{\text{calc}} - P_{\text{rot}}$ are plotted against $B - V$ in Figure 3. A concentration of data points falls on the line $P_{\text{calc}} - P_{\text{rot}} = 0$, reinforcing the consistency between $P_{\text{rot}}$ and $P_{\text{calc}}$. A number of stars at the lower left corner of the graph have low $B - V$ values and negative residuals. They are rotating slower than predicted, indicating a potential Maunder Minimum.

Figure 4 is a plot of $B - V$ versus $P_{\text{rot}}$. As $B - V$ decreases, the amount of scatter along the $P_{\text{rot}}$ axis increases. At high values of $B - V$ (0.70-0.80), $P_{\text{rot}}$ is confined to a relatively narrow range of 0-20 days. As $B - V$ values approach 0.55 from 0.70, scatter approaches a range of 0-85 days. Since the increasing scatter is a function of decreasing age, $P_{\text{rot}}$ is more useful for identifying relative ages of older stars.

These results are likely to be quite accurate because they reflect the findings of Noyes et al. (1984) in the Vaughan-Preston gap. This is a relation in which younger stars tend to be more unpredictable in their rotation periods and activity levels—as compared to older stars. They have a wider spread along their curve than older stars do in an $R'_{\text{HK}}$ versus $P_{\text{rot}}$ plot.

An additional implication is that rotation period is independent of spectral type. These results conflict with Noyes’ determination of $P_{\text{rot}}$. This determination may be derived from Noyes’ algorithm linking stars’ dynamo field generation and Rossby number, or $P_{\text{rot}}/\tau_{c}^{1.5}$ Tau equals convective turnover time, which is a function of mass. Mass, however, is a function of spectral type. Hence, this study would implicate eliminating $\tau_{c}$ from future predictions of $P_{\text{rot}}$.

An illustration of the trends described above is provided in Figure 5, a histogram of rotation periods for the sample. At lower rotation periods, a high number of stars is found. As the graph moves toward longer $P_{\text{rot}}$, a tail in the graph becomes evident. This tail is tapered, meaning that fewer stars exhibit high rotation periods. The percentage of slow rotators approaches 50%. A possible explanation is that as stars age, the increasing numbers of mechanisms for angular momentum transport cause a larger spread in $P_{\text{rot}}$ (Donahue 1993).
Finally, the relationship between a star’s age and its rotation period may be confirmed in Figure 6. The activity index, $S$, has been expressed in $\log R'_{\text{HK}}$ units to provide a measure of magnetic heating (Noyes et al. 1984). $\log R'_{\text{HK}}$, which is chromospheric emission minus any possible photospheric contribution, is plotted against $\log P_{\text{rot}}$. A strong distribution of stars falls along a line of negative slope (with power $\sim 1$), which illustrates a possible power-law relationship between activity (age) and $P_{\text{rot}}$. If the power law is close to 1, it suggests that $R'_{\text{HK}} \propto P^{-1}$.

Three stars are found above the range of the main graph, but they fall on a line of parallel slope. These stars rotate slowly (indicating older solar-type stars) but emit high levels of Ca II (indicating younger solar-type stars)—perhaps these are the RS-CVn stars. An even more prominent cluster of data points falls below the main relation. These are older stars with uncharacteristically small rotation periods (see Figure 3). This phenomenon deserves further investigation. These stars are unusual because their activity levels are low (indicating older solar-type stars), yet they spin quickly (a characteristic of younger solar-type stars).

**Errors and Improvements.** As with any astrophysics research project, the accuracy of measurements made is limited by several factors. These factors include the potential inclination angles of the stars to the line of sight of the observer. An active region (or zone of high convective turnover rate) occurring before or after another one on the visible disk may also interfere with data, as might the difference in $P_{\text{rot}}$ at different latitudes of the stars (Morfill et al. 1991). Differential rotation adds uncertainty to the observed $P_{\text{rot}}$, but may contribute to the process of age determination (Donahue 1993).

Although $P_{\text{rot}}$ and $P_{\text{calc}}$ agree for most stars with $P_{\text{rot}} < 20$ days, the $|P_{\text{calc}} - P_{\text{rot}}|$ can be large for some slowly rotating stars. This implies an error in either $P_{\text{calc}}$, $P_{\text{rot}}$, or both. Increasing the quantity and quality of observations will illuminate the source of these errors.

To obtain more accurate measurements of rotation periods, an increased frequency of observations is needed. The data sample may be reduced to the 51 best stars or the 51 least well-observed stars. Then, a commitment to observe the stars every night must be made. If abandoning a pool of 51 stars is undesirable, staggering the stars in batches of 10, 15, or 25, for alternating years is an alternative. For example, a study of surface differential rotation would require heavy observation of the stars with good periods, while a study searching for a broad range of periods would entail scrutiny of the less well-observed stars.

Examining the 102 stars by hand is a rate-limiting step of the data processing. Computer routines can be developed to refine the discrimination with which automated periodogram analysis and selection of interval are completed. The main drawback to automated data processing is the high degree of experience and judgment needed to select an appropriate interval for analysis; improved programs, however, could alleviate the problem and save time.

**Conclusions**

The relationship between stellar rotation periods ($P_{\text{rot}}$) and relative ages of stars in a sample of Sun-like stars was examined, using the empirical link between activity level and age to calibrate the ages. Data from the last 15 years of observation in Mount Wilson Observatory’s HK Project were used. This consisted of time-series plots of Ca II H and K chromospheric emissions separated by at least 80 days. Fourier transform periodograms of the data were performed to determine $P_{\text{rot}}$ for each star; each of the 102 stars received at least five comprehensive reviews.

Fifty-one stars were found to have measurable rotation periods—a significant improvement over past studies, where $P_{\text{rot}}$ of stars were reported in batches of only 15 or 20. The majority of these stars exhibited increasing $P_{\text{rot}}$ as a function of increasing age. However, anomalies were discovered as well: outliers of older stars that rotated too quickly, and younger stars that rotated too slowly.

The implications of these first results are fivefold. First, younger stars rotate faster than older stars, as has been predicted previously. Second, the anomalies are most likely the result of unrefined data collection methods at Mount Wilson Observatory. A recommendation would be to increase the quantity, quality, and regularity of observations—this will decrease the False Alarm Probabilities of the rotation periods. Third, the anomalies could also signify stars in their activity maximums or Maunder Minimums, which are low
points in their centuries-scale activity flux. Fourth, these results reflect a Vaughan-Preston gap—a relation in which younger stars exhibit wider spread in \( P_{\alpha} \) than older stars do in an H-K flux (\( R'_{\alpha} \)) versus \( P_{\alpha} \) plot. This not only supports the Vaughan-Preston relation, but also supports the accuracy of the rotation periods found.

Fifth, and perhaps most significant, this study finds no correlation between a star’s \( B - V \) and its rotation period. Previous studies (e.g., Noyes et al. 1984) have fitted functions to calculate age from Rossby number, a coefficient equal to \( P_{\alpha} / \tau \). Tau, or convective turnover time, is a function of \( B - V \) spectral type. When the residuals between calculated rotation periods (calculated using a derivative of the Noyes formula) and observed rotation periods were plotted against \( B - V \) large scatter occurred. This indicated that rotation periods are independent of spectral type. That is to say, rotation periods of stars of particular spectral types exhibit relative rates of decline of rotation period with age. Although one may certainly correlate spectral type with age, it is not to be done in a model that incorporates both \( B - V \) and color.

The study of the rotation periods of lower main sequence stars will afford us greater insight into the life cycles of these stars and their evolution on and off the main sequence. Identifying the characteristics of these stars will also isolate conditions for the origin of life on planets orbiting these stars. Comparing the various age determination methods of stars available (the next step in this study would be to compare these results against metallicities, isochrone ages, activity cycle and long-term Ca variability) will enable us to improve these methods. Ultimately, one could take a “snapshot in time” of an LMS star and be able to identify it as relatively older or younger than the Sun. A lower limit for the age of the Universe could be verified.

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Endnotes

1. First, the absolute magnitude, or \( M_j \) of the sample solar-type stars (lower main sequence, or LMS) is plotted against their \( T_{\text{eff}} \). Second, \( \delta M_j \) the difference between \( M_j \) and zero-age main sequence (ZAMS), is calculated and plotted against \( T_{\text{eff}} \). The accuracy of isochrone ages for LMS stars are tested by analyzing clusters of stars—those in the Hyades and M67, for example, should have the same isochrones within each cluster.

2. \( S = \alpha [ ( H + K ) / ( V + R ) ] \), where \( H \) and \( K \) are the Ca II passband counts and \( V \) and \( R \) are the violet and red continuum band counts. \( \alpha \) is a calibration factor called lamp correction that changes nightly.

3. \( \text{FAP} = 100 \{ 1 - (1 - \exp(-z / \rho^2)) \} \), where \( \rho^2 \) equals the total data variance and \( N \) equals the independent frequencies, estimated using Horne and Baliunas’ technique (1986).

4. In the 17th century, the Earth experienced a Little Ice Age. French paintings from this era depict frozen rivers that never freeze over today. During this same time, Maunder observed abnormally low energy output from the Sun (and established a basis for the solar-terrestrial connection). Hence, error mean \( S \) is up to 33.3%, because stars spend one-third of their lifetimes in Maunder Minimums.

5. \((5) \log( P / \tau) \equiv \langle R'_{\alpha} \rangle = 0.324 - 0.400 y - 0.283 y^2 - 1.325 y^3 \), where \( \alpha = 1.9 \), and \( y = \log \tau [K (B - V)] \).

6. Net chromospheric emissions (in log \( R'_{\alpha} \)) have been empirically linked to ages of stars (Soderblom et al. 1991, Donahue 1993).

References


