An Observational Look at Rotating Stars

Stellar Structure and Evolution

Rachel Matson

ASTR 8100

I. Introduction

Rotational velocities of stars provide important clues to how stars form and evolve. Although rotation has traditionally been a second order effect in stellar evolution, its importance has long been recognized. The study of stellar rotation dates back to the time of Galileo when the relationship between sunspots and the rotation of the sun was first observed. Since then, various techniques have been implemented to determine the rotational velocities of various types of stars, in order to better understand the formation and evolution of stars, abundances, stellar mixing, and the distribution of stars on the HR diagram. Such observations have demonstrated the wide range of rotational velocities in stars of differing ages and masses, as well as general trends in both. The dependence upon spectral type for instance, is demonstrated through the mean projected equatorial velocities of main-sequence stars. The velocities increase slowly with spectral type to a maximum near 200km/s in the late B-type stars, and then slowly decrease to F0, before dropping rapidly through the F-type stars (Tassoul 2000). Some observable parameters for high and low mass stars as well as overall trends are presented.

II. Observational Techniques

Periodic Variation in Light Output-

Stellar rotation has been measured observationally for more than two centuries. Although Galileo advocated that sunspots were "dark markings on the surface of a rotating sun," it was nearly three hundred years later before Boulliaud suggested that variations in the light from other stars might be a direct consequence of axial rotation (Tassoul 2000). Today, photometric studies examine the modulation of a star's light due to surface inhomogeneities, such as spots or plages. If observable, the modulation frequency is a direct estimate of the star's rotation period P_{rot} (Mandel & Herbst 1991). Similarly, measurements can be made of periodic variations in the strengths of emission lines that are enhanced in localized active regions of the chromosphere. The advantage of such techniques, is their capability to determine the rotation period and velocity at a much higher precision than v sin *i,* their independence from the projection angle i (Tassoul 2000), and their applicability to slowly rotation stars where Doppler broadening is undetectable (Terndrup 1999).

Spectroscopic Line Broadening-

A second method for determining rotational velocities exploits the broadening of stellar spectral lines due to rotation. The Doppler Effect induces a shift at each end of the star's spectrum as one limb recedes, while the other is advancing. The net effect is a smeared or broadened absorption feature caused by the gradually differing radial velocities and the resulting shifts in wavelength from the various parts of the star (Kaler 1989). Abney demonstrated this effect in 1877, proposing that rotation of a star would result in broadening of spectral lines such that "…other conditions being known, the mean velocity of rotation might be calculated, or perhaps even the angular velocity" (Abney 1877).

The component of the radial velocity observed through line broadening depends on the inclination of the star's pole to the line of sight. The derived value is the projected rotational velocity, or v sin *i*, where v is the rotational velocity at the equator and *i* is the inclination. However, i is not always known, so the result gives a minimum value for the star's rotational velocity (Tassoul 2000). For randomly oriented rotation axes, one can convert the average projected equatorial velocity for a group of stars into an average velocity, using the fact that the average value of sin *i* is $\pi/4$ (Kaler 1989).

When using broadened spectral lines to measure the projected velocity, it is important to examine other sources of broadening that may alter the derived rotation. However, since all lines are made wider in the same characteristic way, there is little confusion with luminosity or pressure effects (Kaler 1989). There is however, more than one mechanism capable of broadening stellar lines. Stellar rotation as well as atmospheric motion, such as micro- or macroturbulence, can account for the broadened profiles observed. Microturbulence can be caused by turbulence in the outer atmosphere of a star, and varies with both effective temperature and surface gravity. When examined by a spectroscope, the velocity of the convective gas along the line of sight produces Doppler shifts in the absorption bands. The distribution of these velocities, along the line of sight, produces microturbulence broadening of the absorption lines. Efforts to reproduce observed broadening through calculation of the shapes of narrow line profiles broadened by rotation alone results in profiles very similar to those observed. In the same way, when line broadening is treated as a "convolution of an 'intrinsic' flux profile with some broadening function," macroturbulence leads to a profile very much like that of a rotationally broadened profile (Conti & Ebbets 1977). Thus, raising questions about which mechanism is the dominant cause of observed broadening. Using spectroscopic studies of O-type stars, Conti and Ebbert found rotation alone to be insufficient, suggesting turbulence is likely necessary in evolved O stars (1977).

The first list of rotational velocities using spectral line broadening was determined by Elvey (1930), using a graphical method proposed by Shajn and Struve (1929). This method divides the data set by similar spectral types and luminosities, and then assumes the flux profile of a sharp-lined star in each group is not influenced by rotation, setting its lines as zero-velocity profiles. These profiles are then broadened mathematically, often taking into effect continuum limb darkening, gravity darkening, differential rotation, electron scattering, etc. This approach, while useful, is problematic in its assumption that the stars being used as zero-velocity profiles have no broadening. In addition, the reference stars really only apply to stars of the same spectral type and luminosity class (Conti & Ebbets 1977). A second approach following the same principles, begins with theoretical profiles computed from intensity profiles, divides the apparent stellar disk into a large number of small areas, Doppler shifts the profile by an amount determined by the projected velocity of that area, then sums over the disk to derive the resulting flux profile. This method, accordingly, accounts for "center-to-limb variations of both the line strength and the profile" (Conti & Ebbots 1977).

Another approach used to extract projected rotational velocity from broadened spectra, useful in the ultraviolet as blending effects make standard profile fitting difficult, involves cross-correlation of a narrow-lined star with a test star. This will produce a cross-correlation function that represents a "superline" of the test star, whose width is related to the line width of both the test star and that of the narrow-lined star. Once a "superline" is created for a test star with a known rotational velocity, a relationship between the width of the "superline" and V sin *i* can then be determined (Penny 1994).

Interferometry-

As demonstrated above, stellar rotation has been measured observationally for more than a century. Up until now, however, virtually all observational evidence underpinning the theoretical models has been based upon velocities inferred from spectroscopic line broadening. While this technique is both well understood and well developed, it is susceptible to confusion with other influences upon spectral line widths, such as various turbulence mechanisms and latitude dependencies of line emission. An independent means by which to determine the parameters governing the structure of centrifugally distorted stars is possible through interferometric measurement of rotating stars (van Belle 2001). From the radius data obtained of a rotating star, such as Altair, models are constructed based upon rotation and polar radius, which are sufficient to map the entire surface as a function of stellar colatitudes and longitudes. From each member of this family of models, derived values for angular velocity, equatorial radius, equatorial velocity, and apparent rotation velocity v sin *i* may be derived. This interferometric measurement of v sin *i* is independent of spectroscopic and photometric means that have characterized all previous rotational velocity measurement techniques. Furthermore, this technique, with sufficient data sampling around a stellar limb, has the potential to recover the inclination of rapidly rotating stars.

III. Effects of Rotation on Observable Parameters

Deviation from Sphericity-

In a rotating star, the most conspicuous effect of rotation is the distortion into an oblate shape. The centrifugal forces reduce the effective gravity according to the latitude, causing deviations from sphericity. An extreme example of an equatorial bulge is found on the star Regulus A (α Leonis A). The equator of this star has a measured rotational velocity of 317 ± 3 km/s. This corresponds to a rotation period of 15.9 hours, which is 86% of the velocity at which the star would break apart. The equatorial radius of this star is 32% larger than its polar radius (McAlister et al 2005).

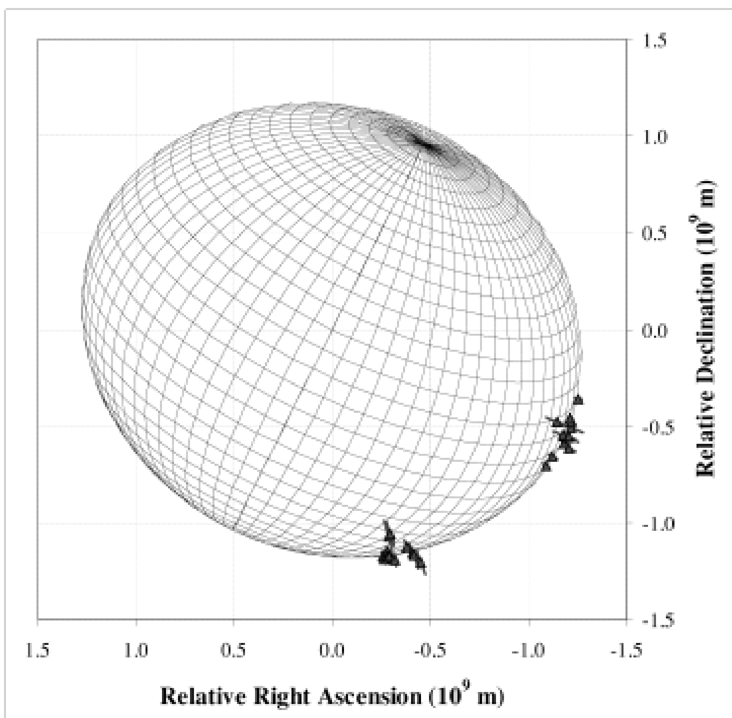

Figure 1-Example three-dimensional model of Altair projected onto the sky [u=0.82, i = 70] (Van Belle 2006)

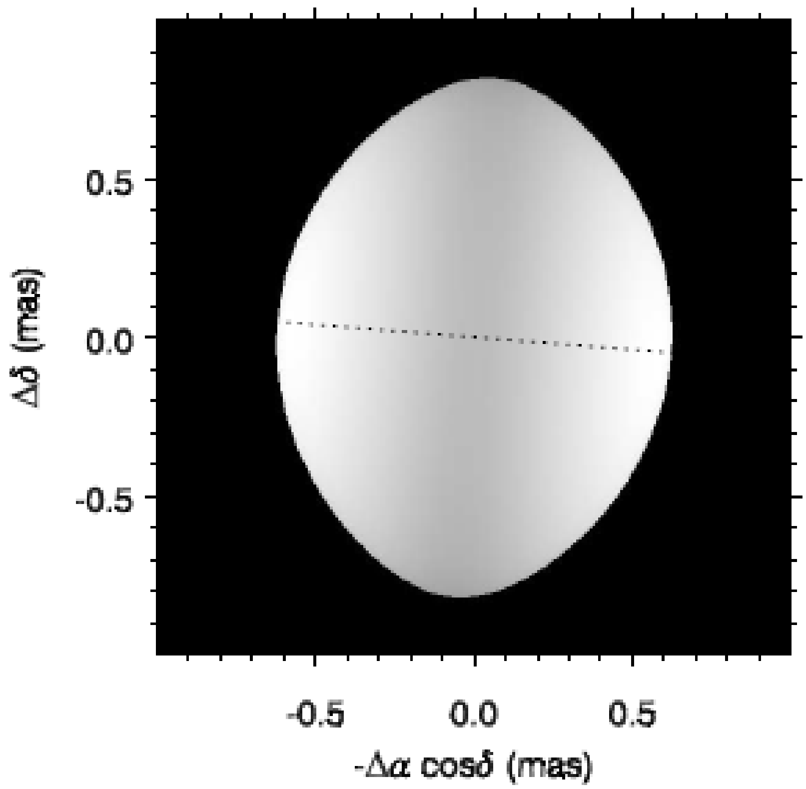

Figure 2-K band image of Regulus in the sky [i=90, beta=0.25, alpha = 85.5] (McAlister 2005)

Gravity Darkening-

Changes in the star's shape and luminosity (flux is proportional to surface gravity) are also mirrored in local effective temperature and surface brightness. As changes in surface effective gravity are smaller at the equator than the poles, the surface brightness and temperature are similarly lower at the equator (Tassoul 2000). For a rapidly rotating star, this phenomenon takes on an additional latitude dependence, often referred to in the literature as gravity-darkening or gravity brightening. As first shown by von Zeipel (1924), the polar zones of stars distorted by rapid rotation will be hotter than their equatorial zones, as the poles are closer to the center of the star. The consequential nonuniform flux distribution over the stellar surface affects a star's visibility curve. For a slowly rotating star, this effect is independent of stellar latitude and is observed to be an increased dimming of the stellar disk from center to limb. For example, Altair's relatively compact stellar atmosphere, the general effect of compositional limb darkening upon the observed visibility curve out to the first null is negligible at 2.2 km (van Belle 2001).

IV. Massive Stars

Evolution-

Early-type stars begin their lives on the main sequence with a broad range of angular momentum, reflected in rotationally broadened spectral lines. The figure below depicts the distributions of rotational velocities for main sequence, giant, and supergiant stars determined via profile fitting of broadened spectral lines of O type stars (Conti & Ebets 1977).

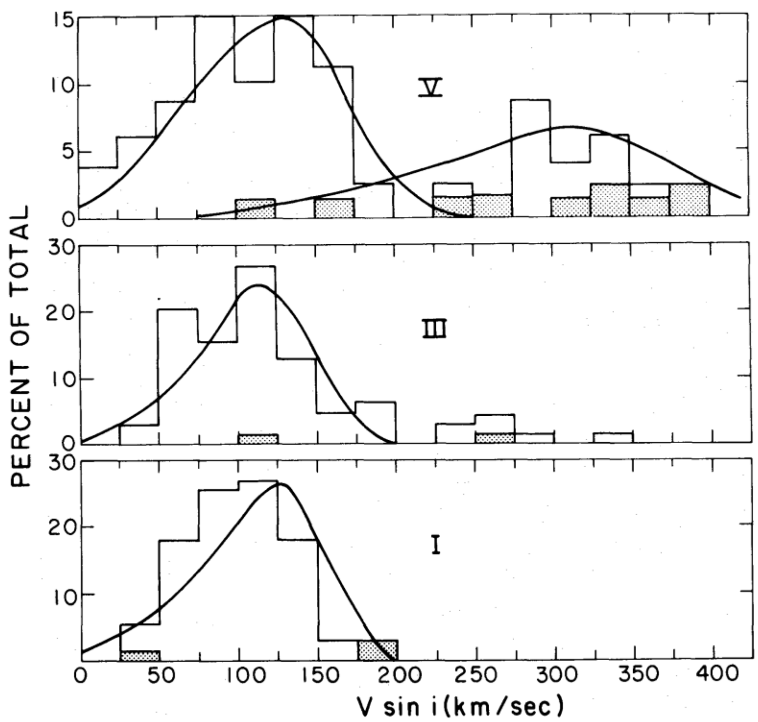

Figure 3-Distribution of Rotational Velocities (Conti & Ebbets 1977)

As the stars increase in radius and luminosity while evolving off the main sequence, the larger radius results in a slower photospheric rotational velocity. Differential rotation in the radial direction and increased luminosity destabilize the envelope, resulting in large-scale macroturbulence. Among the now slowly rotating evolved stars, macroturbulence is the major broadening agent. The figures below illustrate the effect of turbulence, as they evolve the main sequence stars by doubling the radius and simulating the onset of macroturbulence with a velocity parameter of 20km/s.

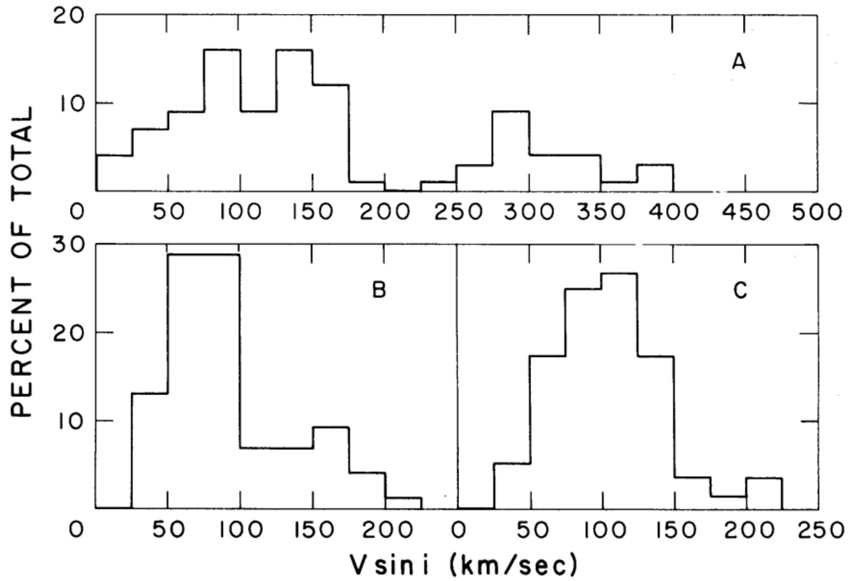

Figure 4- (A) observed MS distribution, (B) distribution calculated from A, (C) observed supergiant distribution (Conti & Ebbets 1977)

Metallicity Dependence-

Mass loss and rotation also play a crucial role in the evolution of massive stars. Fast rotation may lead to enhanced mass loss, while stellar winds cause loss of angular momentum, leading to spin down. In the Galaxy, spin down is believed to be relatively rapid, altering the rotation rapidly so that the initial velocity properties are lost in a few million years (Meynet & Maeder 2000). However, in an environment such as the Small Magellanic Cloud (SMC) where the metallicity is lower, it is believed that stars will retain their initial rotational velocities during their main sequence lifetime, as stellar winds are thought to decrease with lower metal content (Mokiem et al 2006). For early-type stars in the SMC, Mokiem et al compare the distribution of the projected rotational velocities of the SMC objects using cumulative distribution functions (cdfs), which describes the distribution of v sin *i* by giving the fraction of objects with lower or equal velocities. When examining the cdf's for unevolved objects, i.e. luminosity class IV and V, and evolved objects, i.e. luminosity class I, II and III, in the SMC, there are noticeably more fast rotators in the group of unevolved objects. This trend is also seen in Galactic O-type stars, as Penny et al (2006) find relatively more slow and fast rotating stars among the unevolved group.

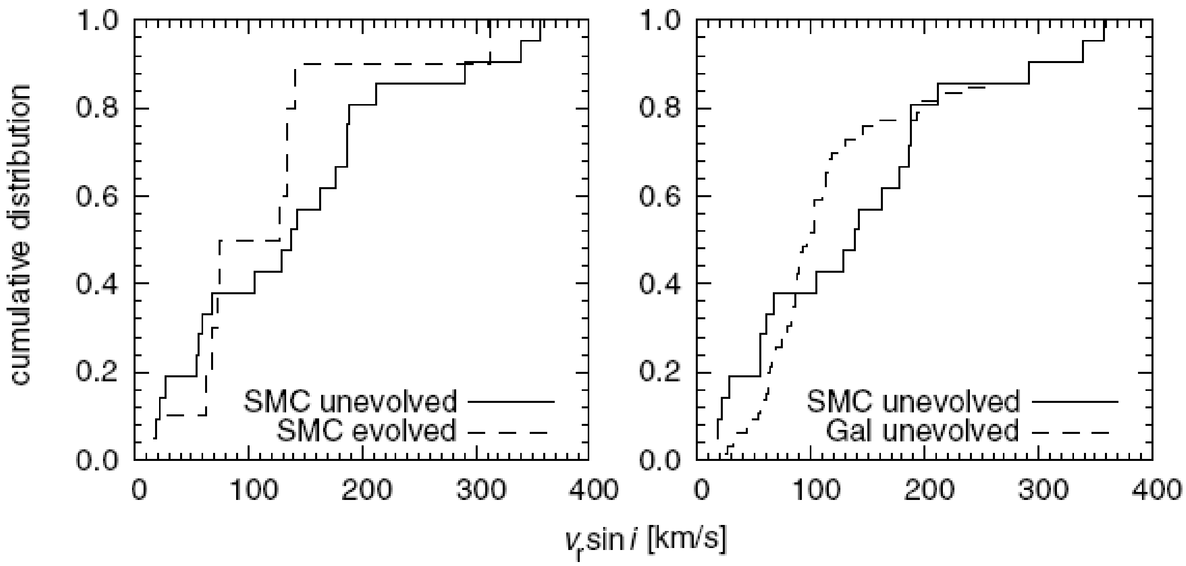

Figure 5-Comparison of v sin i distributions (Mokiem et al 2006)

The figure on the right illustrates this comparison between Mokiem et al (2006) and Penny (1996), showing a marked difference in the curves, as the Galactic curve lies above the SMC between 90 and 190 km/s, implying a lower v sin i. This behavior is consistent with SMC stars experiencing less spin down due to mass loss and weaker stellar winds (Mokiem et al 2006). However, the behavior outside of this velocity range does not appear to follow the trend of spin down due to winds.

IV. Lower Main Sequence Stars

Evolution-

The study of stellar rotation during the pre-main sequence and zero age main sequence phases provides clues to the angular momentum problem of star formation and evolution of circumstellar disks (Tassoul 2000). At later stages, the redistribution of angular momentum within the disk and angular momentum loss by magnetically driven outflows and jets become important as well. However, determining rotational velocities for low mass stars is often difficult as their slow rotation exhibits very little line broadening. The spotted surfaces of these rotating stars do make photometric modulation not only possible, but allow for accuracies of one percent for even the slowest rotators. Such studies have therefore become important to studying G, K and M-type stars with masses from substellar to 1.5 M_{sun}. Rotational velocities obtain in this way are typically easy to determine and highly accurate.

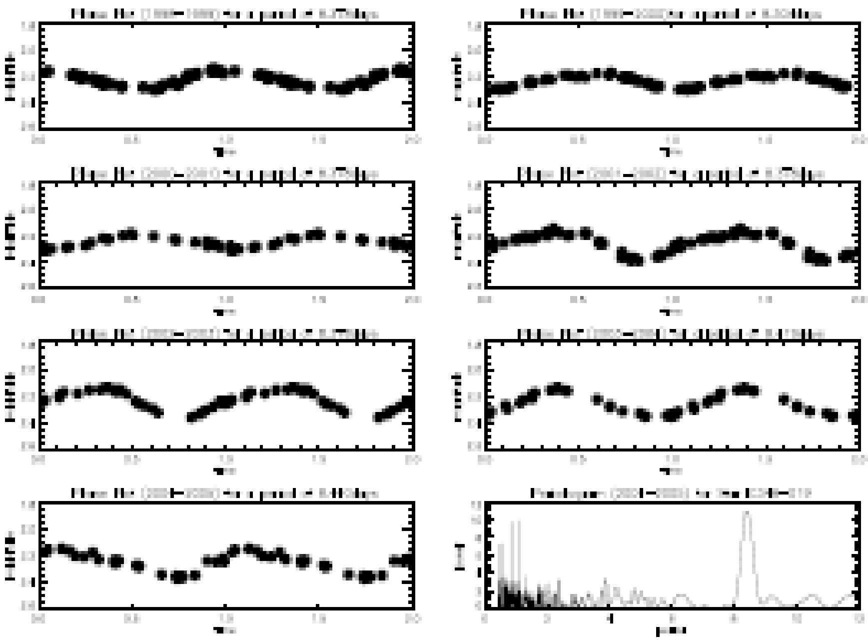

Figure 6-Light curve of HMW 19 based on seven years of photometric monitoring (Herbst et al 2006)

From the nearly 1700 rotation periods now available for low mass stars, some unexpected results have emerged, including the extent of the rotation period distribution and the mass dependency of the measured rotational period distributions. For stars with 0.4 < M < M_{sun} the period ranges from approximately 0.6 to 20 days and is clearly bimodal.

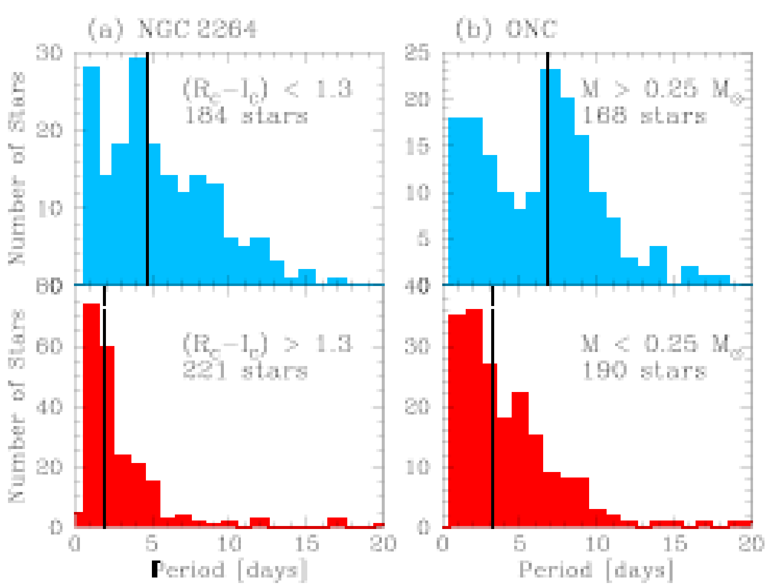

Figure 7-Rotation Period Distribution in NGC 2264 and the Orion Nebular Cluster divided by mass range (Herbst 2006)

The above figure demonstrates the bimodal quality of the data as well as the longer rotation periods of stars in the Orion Nebular Cluster (Herbst 2006)

A similar study by Terndrup (1999) monitored low-mass stars and brown dwarfs in the Pleiades. They were able to derive rotation periods for two of the low-mass stars, verifying that some stars near the Hydrogen–burning limit have large spot groups. The frequency of the spots is low (about 20%-25%), or the spots have temperatures that are near that of the photosphere in these cool stars.

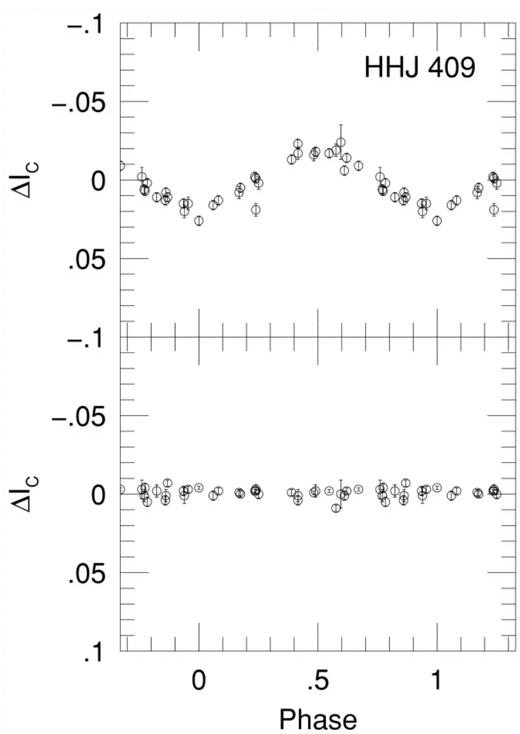

Figure 9-Photometry for HHJ 409 (top) and for a nearby star of similar brightness (bottom) (Terndrup 1999)

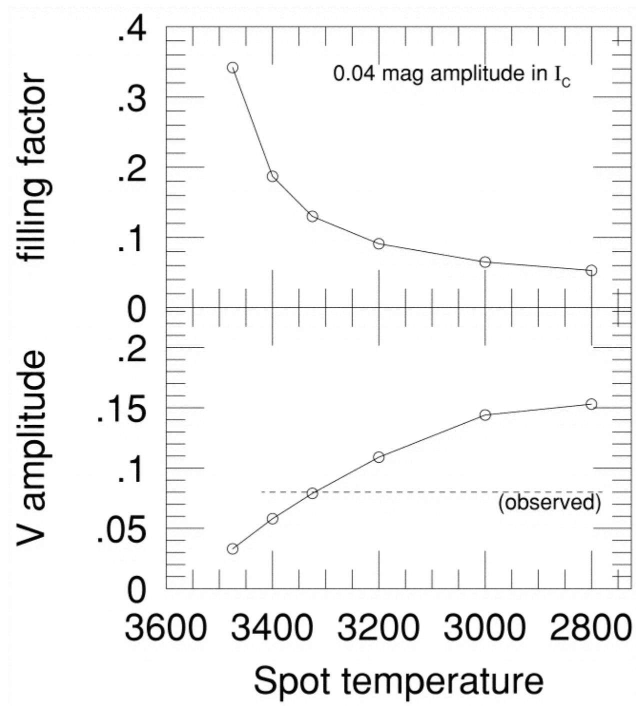

Figure 8-Simple model of blackbody spots for HHJ 409. Top, the filling factor required to produce a 4% variation in IC for different spot temperatures; bottom, the expected V amplitude for different spot temperatures (Terndrup 1999)

Chromospheric Variations-

A similar application of modulation was used to measure the H and K emission lines found in lower main sequence stars. In his study of chromospheric variations in main sequence stars, Wilson (1978) called attention to observed “chromospheric flux variations” that might contain a periodic component due to rotational modulation. (Vaughan et al 1981). Vaughan et al were able to demonstrate the this rotational modulation does occur at a discernable level, as well as determine that the “short-term” fluctuations observed in the H-K flux are largely produced by rotation. In their survey, clearly defined rotational modulation were see in twenty out of twenty-five stars, indicating lower main sequence stars spend a large fraction of their time with asymmetric distributions of active regions on their surface (Vaughan 1981).

V. Conclusion-

Rotating stars, although studied for centuries, remain a fundamental area of study because of their dominance in stellar evolution and properties of the HR diagram. Further progress requires more studies of the physical effects of rotation, in particular the various instabilities that can produce mixing of the elements and transport of angular momentum, in early and later phases of evolution.

References

Abney, W. De W. 1877, *MNRAS*, 37:278.

Conti, P.S. , & Ebbets, D. 1977, *AJ*. 213:438-447.

Kaler, James B. 1989. *Stars and Their Spectra*. Cambridge University Press, New York.

Mandel, G.N. & Herbst, W. 1991, *ApJ*. 383: L75-L78.

Meynet, G. & Maeder A. 2000, *A&A*. 361:101.

Mokiem, M.R., et al, 2006. *A&A*. 456: 1131-1151

Penny, L.R. 1996, *ApJ*. 463:737-746.

Penny, L.R. & Gies, D.R. 2004, *AJ*. 617:1316-1322.

Tassoul, Jean-Louis. 2000. *Stellar Rotation*. Cambridge University Press, New York.

Terndrup, D.M., Krishnamurthi, A., Pinsonneault, M.H., & Stauffer, J.R. 1999, *AJ*. 118:1814-1818.

Vaughan, A.H. et al. 1981, *ApJ*. 250:276-283

Von Ziepel, H. 1924, *MNRAS*. 84:684-701