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Long-Term Datasets for the Understanding of Solar and Stellar Magnetic Cycles
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A Stellar Perspective on the Magnetic Future of the Sun

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Abstract. After decades of effort, the solar magnetic cycle is exceptionally well characterized, but it remains poorly understood. Pioneering work at the Mount Wilson Observatory demonstrated that other Sun-like stars also show regular activity cycles, and identified two distinct relationships between the rotation rate and the length of the cycle. The solar cycle appears to be an outlier, falling between the two stellar relationships, potentially threatening the very foundation of the solar-stellar connection. Recent discoveries emerging from NASA's Kepler space telescope have started to shed light on this perplexing result, suggesting that the Sun's rotation rate and magnetic field are currently in a transitional phase that occurs in all middle-aged stars. We have recently identified the manifestation of this magnetic transition in the best available data on stellar cycles. These observations suggest that the solar cycle is currently growing longer on stellar evolutionary timescales, and that the global dynamo may shut down entirely sometime in the next 0.8-2.4 Gyr. Future tests of this hypothesis will come from ground-based activity monitoring of Kepler targets that span the magnetic transition, and from asteroseismology with the TESS mission to determine precise masses and ages for bright stars with known cycles.

Keywords. stars: activity—stars: evolution—stars: magnetic fields—stars: rotation

1. Context

The Sun is just one of a hundred billion stars in the Milky Way galaxy. Our front row seat on the Earth allows us to observe the Sun in much greater detail than is currently possible for other stars. However, these observations only provide one snapshot in the life story of stars like the Sun. To piece together the whole story, we need to study other Sun-like stars that are younger and older. Observations from the Kepler mission have revealed something unexpected about the life story of stars that never could have come to light by studying our Sun in isolation.

2. Stellar Evolution

Rotation and magnetism are usually neglected in introductory courses on stellar structure and evolution. Although stars like the Sun certainly rotate and have magnetic fields, unless either quantity is extreme they will have no discernible impact on the basic stellar properties. However, rotation and magnetism in stars are intricately linked with each other, something noticed by Andy Skumanich at the High Altitude Observatory more than four decades ago. Based on observations of the Sun and a few young star clusters where ages could be estimated, he proposed that both the rotation rate and the magnetic field strength in stars decay with the square-root of the age (Skumanich 1972).

During a total solar eclipse, you can see the hot gas surrounding the Sun that traces the solar wind, a steady stream of material that emanates from the surface. This material also reveals the underlying magnetic field, often dominated by a strong bi-polar structure. The charged particles in the wind follow the magnetic field lines until they reach a sufficient distance to break free. Upon being liberated, the particles carry away their angular

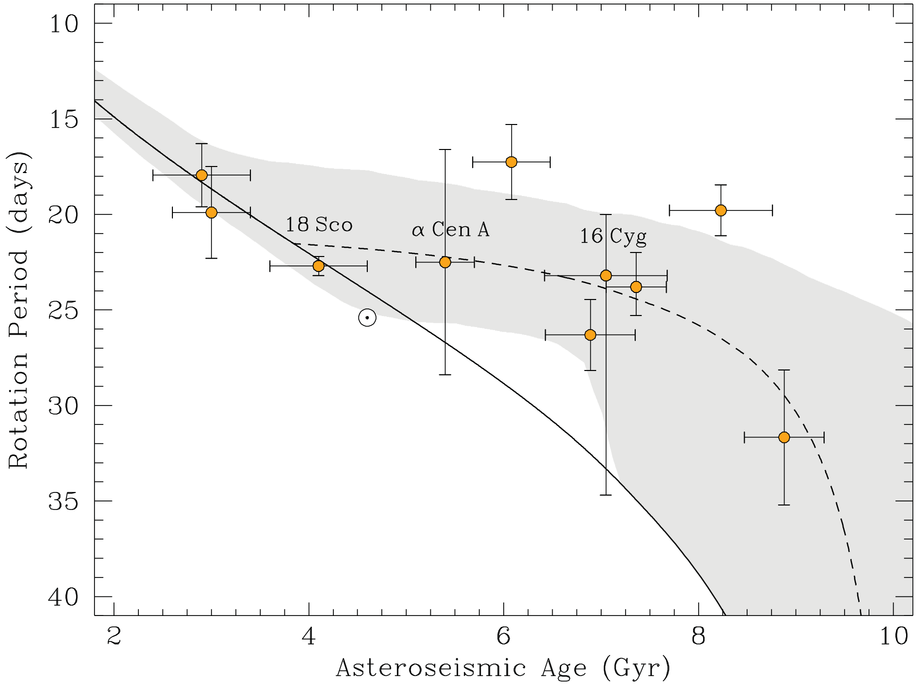

Figure 1. Stellar evidence for the shutdown of magnetic braking in G-type stars. The solid line shows a standard rotational evolution model, which is calibrated using young star clusters and the Sun. The dashed line shows the modified model of van Saders *et al.* 2016, which eliminates angular momentum loss beyond a critical Rossby number determined from a fit to Kepler field stars with precise asteroseismic ages. The shaded region represents the expected dispersion due to the range of masses and metallicities within the sample. A few bright solar analogs are labeled.

momentum and gradually slow the rotation of the star, a phenomenon called magnetic braking. In turn, the rotation modifies the magnetic field due to differential rotation: the Sun rotates faster at the equator than near the poles. The resulting shear wraps the large-scale field into smaller twisted loops that later emerge as spots. Over time, rotation and magnetism diminish together, each feeding off the other.

By the late 1980's, astronomers had recognized that magnetic braking is stronger in more rapidly rotating stars. Although stars are formed with a range of initial rotation rates, this forces convergence to a single rotation rate at a given mass after roughly 500 million years in Sun-like stars. The evidence for this scenario relies on studies of rotation in young star clusters at various ages, and until recently the only older star available to test the theory was the Sun.

3. New Observations from Kepler

The Kepler space telescope changed our understanding of how rotation and magnetism evolve in stars like the Sun. After launching in 2009, Kepler spent four years monitoring the brightness of thousands of stars and a few older clusters. Rotation in the star clusters with ages up to 2.5 billion years agreed with previous expectations, but the isolated stars with ages determined from asteroseismic analyses of their oscillations revealed a very different behavior. The younger stars agreed with the clusters, but the older stars were rotating more quickly than expected (see Figure 1). Beyond middle age, the angular momentum of stars no longer appeared to be decreasing over time.

The anomalous rotation became significant near the solar age (4-5 billion years) for G-type stars like the Sun, but it appeared after 2-3 billion years for hotter F-type stars and after 6-7 billion years for cooler K-type stars. This dependence on the surface temperature suggested a link to the convection zones, where temperature gradients drive the rise and fall of fluid elements whose motions are thought to play a role in the generation of magnetic fields. Specifically, magnetic braking appears to change at a constant Rossby number, defined as the ratio of the rotation period to the turnover time for fluid elements in the convection zone. Cooler stars have deeper convection zones with longer turnover times, so they would continue braking for longer before reaching the slower rotation required to yield a specific Rossby number. In a 2016 Nature paper, Jennifer van Saders and colleagues reproduced the observations with rotational evolution models that eliminated angular momentum loss beyond a critical Rossby number, which all stars reach around the middle of their hydrogen core burning lifetimes (van Saders *et al.* 2016).

Ground-based spectroscopic observations of the Kepler stars quickly revealed that the critical Rossby number could also be interpreted in terms of magnetic fields (Metcalfe *et al.* 2016). It turns out that two specific spectral lines from calcium ions can serve as a useful proxy for the strength and fractional area covered by magnetic fields. The critical Rossby number is equivalent to a specific level of calcium emissions from the chromosphere, the part of the solar atmosphere just above the light-emitting photosphere. Stars with different surface temperatures take different amounts of time to reach this level of chromospheric emission.

Even though the shutdown of magnetic braking locks the stellar rotation rate in place, chromospheric emission continues to decrease as a star ages. The disruption of magnetic braking could be understood if the global field were concentrated into smaller spatial scales, which are much less efficient at shedding angular momentum. The critical Rossby number corresponds to a rotation rate that is slower than the convective turnover time, leading to a diminished imprint of Coriolis forces on the convective patterns. This might naturally lead to a change in the character of differential rotation that would modify the dominant scale of the global magnetic field.

4. Demise of the Solar Cycle

The revised theory of rotational and magnetic evolution not only explains the new observations from Kepler, it also addresses a long-standing puzzle about the 11-year sunspot cycle compared to other stars. Figure 2 shows an updated version of a diagram originally published by Erika Böhm-Vitense more than a decade ago. It includes the best observations of magnetic cycles and rotation periods for stars in the Mount Wilson survey, which started in the late 1960's and ran for more than 35 years. Böhm-Vitense noted that there were two distinct relationships between the rotation period and the length of the stellar cycle (solid lines). Most significantly, she found that the 11-year solar cycle appeared to fall between the two stellar sequences (Böhm-Vitense 2007).

Our updated version of the diagram colors the points to indicate the surface temperature of each star, and it shows the rotation periods of a few stars that exhibit constant chromospheric emission with arrows along the top. The critical Rossby number where magnetic braking shuts down corresponds to the rotation periods where stars with various temperatures begin to deviate from the lower stellar sequence (dashed lines), eventually leading to stars with constant chromospheric emission (15 CrB, 16 Cyg A, and 31 Aql). Stars with cycles that were previously considered outliers, including the Sun and α Cen A as well as 5 Ser and 94 Aqr A, can now be understood as transitioning from predominantly large-scale to smaller-scale global magnetic fields.

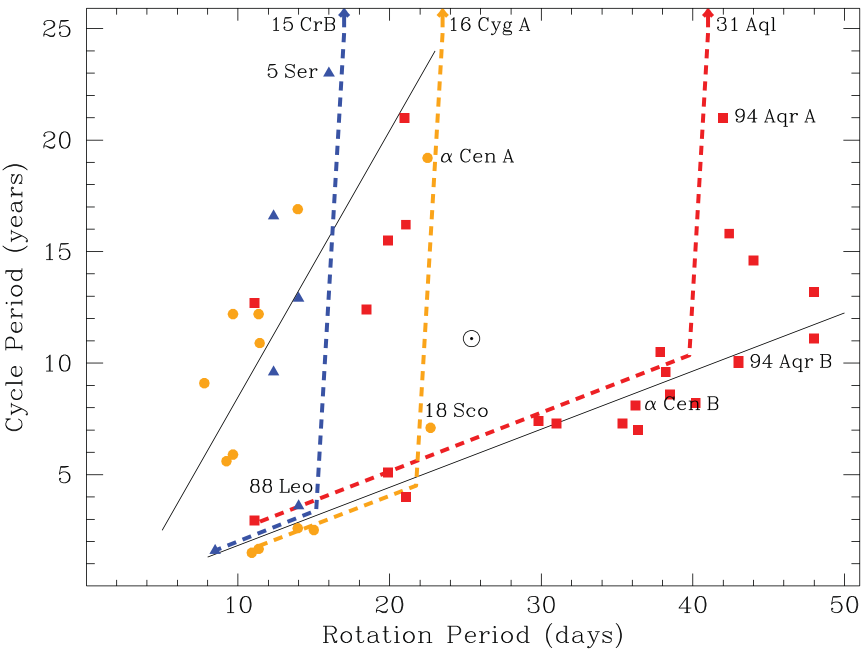

Figure 2. Updated version of a diagram originally published by Böhm-Vitense 2007, showing two distinct relationships between rotation period and the length of the activity cycle (solid lines). Points are colored by spectral type, indicating F-type (blue triangles), G-type (yellow circles), and K-type stars (red squares). Schematic evolutionary tracks are shown as dashed lines, leading to stars with constant activity (arrows along the top) that appear to have completed the magnetic transition.

Considering the evolutionary sequence defined by the solar twin 18 Sco (4.1 billion years), α Cen A (5.4 billion years), and the old solar analog 16 Cyg A (7.0 billion years), the data suggest that a normal magnetic cycle on the lower stellar sequence may grow longer across the transition (yellow dashed line) before eventually becoming undetectable or disappearing entirely. The Sun (4.6 billion years) falls to the right of this evolutionary sequence because it is slightly cooler than the other stars, reaching the critical Rossby number at a longer rotation period (Metcalfe & van Saders 2017).

Future tests of this new theory for magnetic evolution will come from ground-based chromospheric emission measurements of Kepler targets that span the magnetic transition, and from asteroseismology with the Transiting Exoplanet Survey Satellite (TESS) to determine precise masses and ages for the bright stars with known magnetic cycles. Additional insights could also come from more difficult measurements of differential rotation in both samples of stars, and from reconstructions of the global magnetic field geometry obtained from analysis of the polarization of light emissions.

The text above was adapted from an article that will appear in Physics Today magazine.

References

Böhm-Vitense, E. 2007, *ApJ* 657, 486
Metcalfe, T. S., Egeland, R., & van Saders, J. 2016, *ApJ* (Letters) 826, L2
Metcalfe, T. S. & van Saders, J. 2017, *Solar Phys.* 292, 126
Skumanich, A. 1972, *ApJ* 171, 565
van Saders, J. L., Ceillier, T., Metcalfe, T. S., *et al.* 2016, *Nature* 529, 181

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