Magnetic Fields throughout Stellar Evolution
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Stellar Magnetism in the Era of Space-Based Precision Photometry

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Abstract. The advent of precision space-based photometric missions such as MOST, CoRoT and *Kepler* has revealed stellar magnetic activity in unprecedented detail. These observations enable new investigations into the fundamental nature of stellar magnetism by furthering our understanding of the stellar rotation and differential rotation that generate the field, and the photometric variability caused by the surface manifestations of the field. In the case of stars with planetary candidates, these data also offer synergy between studies of stars and planets. Here, I review the possibilities and challenges for deepening our understanding of magnetism in solar-like stars in the era of space-based precision photometry.

Keywords. stars: activity, stars: spots

1. Introduction

Magnetism in solar-like stars is thought to operate via an $\alpha\Omega$ dynamo, where shearing at the interface between the inner radiative and outer convective zones (or "tachocline") creates ropes of magnetic flux (see Reiners 2012 for a recent review of magnetism in solar-like stars). These flux tubes rise buoyantly through the convective zone and protrude from the stellar surface, creating a variety of observable phenomena, from dark starspots at the footpoints of these protruding flux tubes, to flares as magnetic field lines snap and reorganize in the outer stellar atmosphere (Strassmeier 2009). These phenomena create variability on a variety of timescales: from second to minutes to hours for flares, to days, weeks and months as stars rotate and magnetic surface features (such as spots) evolve. The appearance, evolution, temporal and spatial behavior of these features provides direct feedback to theory of the magnetic field generation: the stellar rotation creates the periodic variability that allows observers to measure the rotation and differential rotation that are responsible for the generation of the field itself, and the geometrical distribution of spots, their evolutionary timescales are also predictions of theory (Berdyugina 2005).

Stellar rotation periods are also interesting as a proxy for stellar age via gyrochronology relations, or the relationship between the stellar rotational spindown and age (Barnes 2007). As age is a difficult quantity to measure for individual field stars, the rotation period is often the best (and sometimes the only) existing method for constraining age. In addition to its intrinsic interest to stellar astrophysics, stellar age is also of particular interest for stars hosting exoplanetary systems. Knowing the age of an exoplanet host star provides a timestamp on the exoplanetary system, informing our understanding of the evolutionary history of the system and potential habitability for any planets that lie in the habitable zone.

On the Sun, surface magnetic phenomena are visible in striking detail, both in a spatial and temporal sense. The launch of Solar Dynamics Observatory in 2010 provides the most recent examples of exquisite fine structure evident as these events evolve. However,

data for the Sun is truly unique, in that spatial resolution of these phenomena is difficult or often impossible to achieve for stars besides our Sun. Our knowledge of stellar magnetism is therefore faced with the fact that we study the Sun– the star upon which our understanding of stellar magnetism is based– in a very different way than we study magnetism in the rest of the stars in the Universe. For almost all other stars, only integrated quantities are accessible, and all spatial information must be inferred.

The era of time domain astronomy has brought opportunities to at least crack the temporal resolution of these highly variable events, and in some cases, to obtain surface maps as well. The Mount Wilson survey carved out great first steps in this area, monitoring activity for a number of solar like stars over a very long time baseline from the ground (Duncan *et al.* 1991). However, the advent of space-based time domain surveys in the past decade has breathed new life into studies of stellar magnetism. While photometric surveys themselves are not a new idea, the recent emphasis on such surveys has been partly driven by the search for transiting exoplanets, requiring high precision, high cadence, continuous and long-duration photometry. The potential synergy of such surveys was of course recognized early on: a very early seed of the eventual *Kepler* mission, the abstract of Borucki *et al.*(1985) states "The high precision, multiple-star photometric system required to detect planets in other stellar systems could be used to monitor flares, starspots, and global oscillations."

2. Overview

In the past decade, three space-based photometric surveys have allowed us to see the effects of stellar variability in unprecedented detail: MOST (Walker *et al.* 2003), launched in 2003 and still currently operating; CoRoT, launched in 2006 and completed in 2012 Auvergne *et al.* 2009; and NASA's *Kepler* mission Koch *et al.* 2010, launched in 2009 and in limbo since early 2013 due to a reaction wheel failure† In this proceeding, I focus primarily on recent results from Kepler, though the reader is advised to also seek out the ground-breaking results from the CoRoT and MOST missions.

Stellar rotation can be measured through a variety of methods. In the case of the Sun, rotation and differential rotation are readily apparent by monitoring the passage of sunspots as a function of solar latitude. This surface resolution is also what has revealed the now-familiar "butterfly diagram" where the preferred latitude for the appearance of sunspots changes over the course of the solar cycle, moving from high latitudes during the solar minimum to lower latitudes at the solar maximum. For stars, such detailed surface features are impossible, but the effects of stellar rotation are evident in both spectroscopy and photometry. Line broadening in spectra provides a measurement of $vsini$, or the rotational velocity v modified by the sine of the stellar inclination, i. If the star is viewed equator-on, the velocity can be turned into a true stellar period if the stellar radius is also known. However, stars are not always conveniently equator-on towards Earth, and typically the stellar inclination is unknown. In these cases, $vsini$ provides only a limit on the rotation period. In photometry, stellar rotation is revealed through its modulation of the integrated stellar brightness as surface features rotate into and out of view. In the case of the precise, nearly uninterrupted photometry available from MOST, CoRoT and Kepler, the stellar rotation in many cases is readily evident from even a short sequence of data, provided the starspots modulating the stellar brightness are

† The loss of *Kepler*'s third reaction wheel compromises its ability to perform the fine pointing that made its original photometric precision possible. As of this writing, plans for possible repurposing of the *Kepler* telescope are being considered.

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long-lasting enough that they create a regular pattern of dimming and brightening over the course of several rotation periods. Precise rotation periods can then be determined by applying a Lomb-Scargle periodogram (Scargle 1982), autocorrelation (McQuillan *et al.* 2013), global fitting (Reinhold Reiners & Basri 2013), or other techniques. If spots exist at multiple latitudes, drift in phase due to differential rotation, and are similarly stable over multiple rotations, differential rotation will create clear beat patterns between the different periods in the photometry, and multiple peaks may also be evident in the periodogram. In these cases the primary point of confusion is aliasing in the periodogram, where the periodogram peak with highest power may actually be that of half the true rotation period.

Of course, these cases are ideal, and so are only true for a small number of stars. More typically, the stellar brightness is modulated by spots that evolve on timescales approaching or comparable to the rotation timescale, as well as other surface features such as plage. These more ambiguous cases often require confirmation of the period by eye, to confirm the period found by algorithm (e.g. periodogram or autocorrelation function). In addition, wIthout an absolute measurement of the unspotted stellar brightness, the observed variabiity will be relative, and it is therefore difficult to assess the relative contributions of bright and dark features. There is additional ambiguity created by the geometry of spot distribution over the stellar surface: isolated spot features that rotate into and out of view create a regular pattern of variability, but in the case of a more distributed spot geometry, where stellar spots mottle the surface rather than being in isolated groups, there may not be any time during the stellar rotation where the star is unspotted. In these cases, the variability may be relatively low amplitude, and so without an additional measure of activity (such as spectroscopic observations of the Ca II K line) there may be ambiguity between a star with relatively low levels of activity (and correspondingly few spots) and a star whose surface actually has many spots. One of the benefits of constant monitoring provided by space-based photometry missions is that, even if the spot pattern is not conducive to finding the stellar rotation period at one time, the evolution of the spot pattern may yield a more fortuitous arrangement at some point during the long baseline of the observations (see Fig. 1).

Magnetic activity is intimately related to the stellar rotation and differential rotation, and manifests not only in chromospheric emission but throughout the stellar atmosphere, as well as across the electromagnetic spectrum. Previous surveys of the stellar activity-rotation relation have shown a relationship between the level of chromospheric activity (measured by the Ca II K measure log R'_{HK}) and the Rossby number Ro, or the ratio of the rotation period to the convective overturn time ($\mathrm{Ro} = \mathrm{P}_{rot}/\tau_{conv}$). As shown in Figure 7 in Mamajek & Hillenbrand (2008), activity in solar-type stars decreases as stars spin down over the course of their main sequence lifetimes. Optical photometry traces magnetic effects in the stellar photosphere, where it creates the dark starspots that allow one to measure the stellar rotation in the first place. One might therefore ask whether the photospheric activity, as captured by the amplitude of optical variability, also shows a similar relationship to the stellar rotation as chromospheric activity tracers. Walkowicz & Basri (2013) recently used rotation periods determined for ∼950 host stars of the *Kepler* exoplanet targets to showed that the correlation of photometric variabitliy amplitude and the Rossby number are loosely correlated, but with much greater scatter than the relationship between log $\mathrm{R'}_{HK}$ and Rossby number (see Figure 2 of Walkowicz & Basri (2013)). The authors attribute this scatter to differing spot geometries, such that rapidly rotating, active stars may appear to have low amplitude optical variability despite being quite magnetically active. The range of photometric amplitudes for the *Kepler* exoplanet candidate host stars is comparable to the Sun for similar Rossby numbers, as inferred

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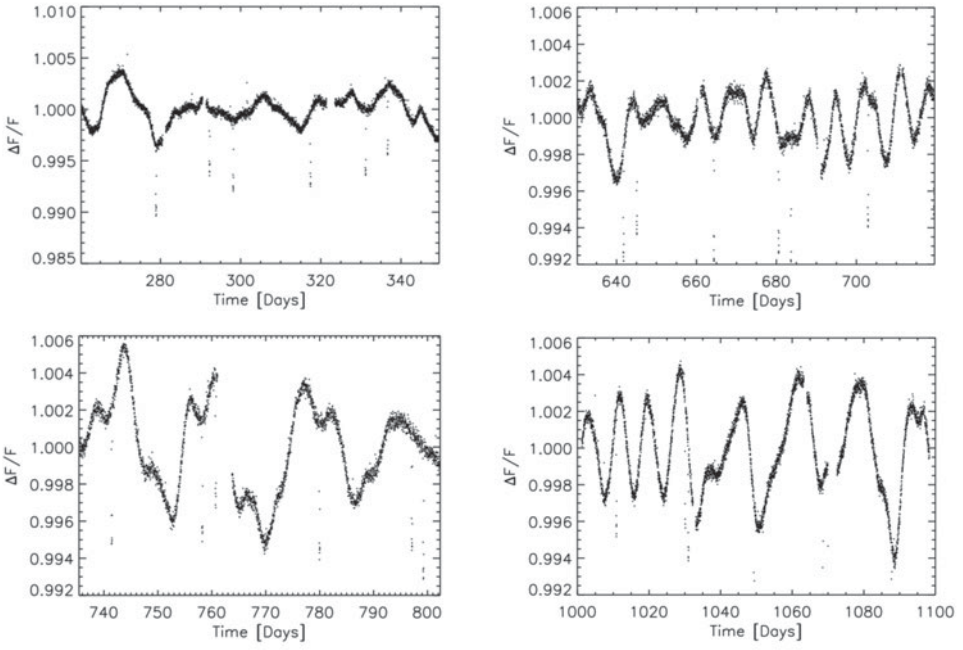

Figure 1. *Kepler* lightcurves for four different quarters of observations of the Kepler-9 system. The evolving spot distribution over the stellar surface causes dramatic changes in the morphology of the lightcurve, making some quarters more amenable to determination of the stellar period than others.

from the amplitude of white-light variability in SOHO Virgo g+r lightcurves (see Basri *et al.* 2010 for details).

Once solar-like stars have arrived on the main sequence, they converge to a well-defined age-rotation relationship, such that the stellar rotation period may be used to infer an age for the star. Indeed, Epstein & Pinsonneault (2012) compare a variety of common dating methods (such as asteroseismology or isochrone fitting), and find that rotation-based ages provide some of the best constraints on stellar age for older (age $>$ 550 Myr) main sequence stars, even when accounting for uncertainties due to differential rotation. At present, gyrochronology relationships are best calibrated for stars younger than a Gyr, due to the fact that rotation periods for older stars with known ages are considerably fewer and further between (with the exception of a single star: the Sun). Clusters observed by *Kepler* (e.g. NGC 6811, Meibom *et al.* 2011) may provide additional constraints on existing gyrochronology relations, increasing confidence in ages derived from rotation in the future. At present, *Kepler* target stars for which rotation periods have been measured tend to be around rotation periods of 30 days or less. This is for a variety of reasons: first and foremost, active, rapidly rotating stars tend to have higher amplitude variability, and their short rotation periods are well-sampled in a single quarter (90 day interval) of *Kepler* data. In addition, the *Kepler* data are detrended to remove systematics caused by spacecraft motion; while the detrending pipeline preserves periodic signals of $\sim$20 days or less, longer periodic signals tend to be attenuated or removed entirely from the lightcurves (Smith *et al.* 2012, Stumpe *et al.* 2012). Therefore, most of the stars that are amenable to rotation period determination thus far are concentrated in stars whose rotation periods are shorter than that of the Sun. For rotation periods beyond $\sim$45 days, or half of the lightcurve, multiple quarters of data must be used to derive the period

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securely. Even so, it may not always be possible to derive a trustable period from the detrended data, as long drifts in stellar brightness that approach the length of a quarter begin to resemble instrumental effects, and are readily removed by the pipeline. For the many more slowly rotating stars amongst the *Kepler* targets, it may be necessary to re-extract the photometry from the pixels to mitigate systematics (e.g. Kinemuchi *et al.* 2012), and to join multiple quarters of data together to fully sample the period.

3. Implications

Ultimately, we must return to the heart of how we relate observable quantities about stellar magnetism, such as rotation and variability in integrated measures of activity, to a physical understanding of what these imply for the generation of the magnetic field. Here again we face the challenge that we lack the detailed surface observations that have so informed our understanding of the Sun, and so it remains challenging to relate observations of other stars to that of our magnetic Rosetta Stone. Space-based precision photometry has provided a new opportunity to map the surface features of stars through modeling of the spot distribution. In the case of stars hosting transiting exoplanets, deformations in the transit shape due to the planet transiting stellar spots can permit a detailed mapping of the stellar surface under the planetary transit chord (Nutzman *et al.* 2011, Sanchis-Ojeda *et al.* 2011, Silva-Valio & Lanza 2011), but only some transits show well-defined features due to spot transits. More often, distributed, evolving spots just create noise in the transit depth of the folded lightcurve, heightening uncertainty in the planet parameters without yielding useful information about the star.

Spot modeling has enjoyed a renaissance over the past decade due to the availability of new precise photometry, but these models can be highly degenerate (see Walkowicz, Basri & Valenti 2013 and references therein), making the problem "ill-posed even when the signal to noise approaches infinity" (K. Strassmeier, as stated during IAU SS13). If the starspot distribution is amenable, the morphology of the lightcurve may provide constraints on the stellar inclination (in that stars seen from lower, more pole-on inclinations will have more gradual spot ingresses and egresses). However, the presence of multiple spots, differential rotation and spot evolution can often confound uniqueness. Even if a resulting model is not unique, such models do provide robust estimates of the total spot coverage as a function of longitude and amount of differential rotation (e.g. Fröhlich *et al.* 2009). When available, complementary methods, such as modeling the complete lightcurve together with detailed mapping of the transit chord for stars with transiting planets, can reveal details of the stellar surface on a variety of scales (Silva-Valio & Lanza 2011). In some cases, it may be possible to know the inclination of the system from spectroscopy (yielding a measurement of vsini and the stellar radius) in combination with the photometric period. In these cases, the degeneracy between latitude and inclination may be broken, yielding information on the latitudinal distribution of starspots.

Rotation periods and differntial rotation have been measured for numerous stars observed by MOST, CoRoT and most recently Kepler. Currently, the most easily accessible rotation periods are for stars with relatively clear cut variability, where the effect of spots is obvious and the rotation period can often be guessed at just by eye. Unfortunately, the variability of our own Sun does not resemble these stars! Viewed in integrated optical light, the Sun's own variability appears far more erratic, with spots that evolve on timescales comparable to the stellar rotation period, as opposed to being stable over the course of several rotations (and thus yielding an uncomplicated determination of the solar rotation period). Faculae also play a large role in the solar variability, modulating the light as they pass across the stellar limb (where they are most visible, unlike spots

whose projected area and thus greatest effect appears as they cross disc center). Numerous stars in the *Kepler* dataset bear a strong resemblance to our own Sun, but these are as yet largely unmined for rotation periods and differential rotation. However, bringing the solar and stellar views of magnetic activity closer together requires that we embrace this challenge.

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