STELLAR ACTIVITY STUDIES WITH EDDINGTON

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ABSTRACT

I present a brief outline of the use of Eddington data for stellar activity studies. The most important stellar parameters that could be obtained from secondary targets within both main science fields are stellar rotation, differential rotation, meridional flows, stellar cycle morphology, spot lifetimes, and flare activity. Due to the vast amount of data, one may hope to find relations between stellar pulsation and magnetic activity, and between stellar flares and the existence of Vulcan-type planets.

Key words: Stars: rotation – Stars: activity – Stars: spots – Techniques: photometry

1. INTRODUCTION

One of the main scientific fields of interest in the stellar-activity context is to map the angular-momentum evolution throughout the H-R diagram. This is done most efficiently by including open clusters of various ages through the detection of rotational modulation signatures, e.g. due to starspots. As we also know from pre-launch studies of similar missions, determining rotational properties of the planet host star is a crucial issue for the correct interpretation of planetary transits. This is because starspots are expected to be the main limitation for the detection probability of planets from around late-F stars down to the L dwarfs. Detecting and monitoring the variable amplitude modulation of such a rotationally modulated signal with an unprecedented level of precision opens up yet another field of interest, namely that of mapping the surfaces of spotted stars from one-dimensional data. From that we could learn more about stellar butterfly diagrams, differential rotation, wind geometries in case of anisotropic winds, the interplay between stellar rotation and non-radial pulsation and, ultimately, the star-planet interaction, a field of virtual no data. I will also stress the importance of having color information in the photometry.

2. ROTATIONAL EVOLUTION OF SOLAR-TYPE STARS

The Sun must have been a rapid rotator during at least a brief stage in its past because angular-momentum conservation only starts from an initial distribution and does not happen instantaneously throughout the protostellar cloud. Using simple virial theorem one can show that for star formation to occur at all most of the initial magnetic flux and angular momentum must be shed at the very beginning. How this would happen and on what time scale would be a very interesting question to answer.

Despite these "initial" problems, the solar rotational evolution in the pre-main-sequence phase is dominated by the disk-star connection and the stellar contraction. This is of course a spin-up, but angular-momentum loss due to wind is going on at the same time. The latter is a strong function of rotation rate and surface magnetic field strength and topology which leaves quantitative models inconclusive if not realistically modelled as an axisymmetric (and possibly non-axisymmetric) MHD wind. Furthermore, the internal connection between a dynamo-generated field in the convection zone and a relic field in the radiative core adds a further mechanism to break down surface rotation, even differentially as shown by Charbonneau & MacGregor (1992) (Fig. 1). Clearly, observations of rotational rates of class 0 (in the FIR though) and class I and II T Tauri's in the optical will constrain the early stages of the solar rotational evolution. Unfortunately, the rotational signal due to magnetic inhomogeneities on these

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1 The switch from spin-up to spin-down is supposed to occur on the ZAMS, or shortly prior to it, and is relatively insensitive to the "initial" conditions.


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Solar-type stars

![Graph showing observed variability for the Sun along the solar cycle.](image)

Figure 2. Observed variability for the Sun along the solar cycle.

Models predict a rapid spin-down due to magnetic braking either on the ZAMS or shortly thereafter. Time scales are on the order of a few years to $10^3$ years depending upon the depth of the convective envelope and the radius of the star. Observations of field sub-giants and giants indicate a pronounced drop of rotational velocities near G2 (Gray 1989 and subsequent papers). A later paper by Schrijver & Pols (1993) suggested a smoother drop of rotational velocity. Unfortunately, these indications are based on $v \sin i$ data or even on running-mean averages from various older catalogues. Directly measured rotation periods may show a slightly different drop of rotation in the rotation-temperature plane than previously claimed. Again, clearly a science case for Eddington.

Fig. 2 shows the well-known solar irradiance variability as measured from a variety of satellites. It is of relevant importance to emphasize that the rotationally modulated signal is of the same amplitude as the cyclic variability and that a too short a time coverage for photometry could lead to spurious rotation periods. This is even more true for very young stars where there will be additional light-curve variations due to a rapidly changing spot distribution. Fig. 3 gives just a glimpse what can be expected from a <1 Gyr old Sun.

3. Rotation of L dwarfs and Brown dwarfs

Are the very cool stars and brown dwarfs also rotating and, if yes, how fast? Are the rotational speeds sufficient to drive a dynamo in these objects? Initial observations of the brown dwarf BRI 0021 with Keck I and II (Basri et al. 2000) verified that such objects tend to be rapidly rotating but display only weak Hα emission. Further data indicate a general trend to higher rotation with lower luminosity. The fastest rotator so far is the brown dwarf Keu-1 with 80 km s$^{-1}$ which implies a rotation period of 90 minutes. The most active object, PC 0025, is a relatively slow rotator. Recently, Basri (1999) suggested a fully turbulent dynamo driven by convection which is quenched when the rotational velocities become too fast in comparison to the convective velocities. With the “deeper” integrations in the planet-search field Eddington may be used for a survey of rotational velocities of brown dwarfs and L-dwarfs as faint as $I = 20$.

4. Stellar cycles

Fig. 5 shows three typical Ca II H&K light curves of solar-type stars along with a light curve of the sun-as-a-star as
obtained within the long-term Mt.Wilson program (courtesy their homepage). We see that stellar cycles not only come in different periods, 3 years to 21+ years, but also with quite different light curve shapes. Stars with low amplitudes but long periods and stars with large amplitudes but short periods are common along with stars with variable amplitudes and stars with clearly detectable variations but no clear periodicity (see e.g. Baliunas et al. 1998).

![Stellar cycles](image)

*Figure 5. Activity cycles for The-Sun-as-a-star (top) and three targets from the Mt. Wilson H$\alpha$K program.*

The *Eddington* data for planet hunting as well as for seismology will be clearly affected by such cyclic changes if they are present. The three year observing window will allow to follow some of these changes but will likely not lead to the coverage of a full cycle for any single target. On the other hand, giant stars may show shorter cycle periods than the main-sequence stars monitored in the Mt. Wilson project. For these stars though, the meaning of “cycle” remains to be determined.

5. Activity-Pulsation connection

If we – again – use our Sun as the model G2V star, we may assume that there is good evidence that the internal structure slightly changes as a function of the activity cycle. Fig. 6 plots the sunspot number counts along with the frequency shifts of all $\ell < 4$ p-modes throughout the solar cycle from 1984 through 1995. Obviously, the average frequency shift increases by almost a factor five from spot minimum to spot maximum.

*Eddington* will provide lower precision frequency shifts for a large number of stars in the background of the fields containing the primary seismology targets. It will be extremely interesting to check these targets for activity signs and, if positive, correlate their frequency shifts with activity signatures obtained from the ground. Sect. 8 suggests some facilities where such an activity survey could be done once the science fields are fixed.

6. Stellar flare – planet connection

Recent success and a first understanding of the role of prominences for the stellar angular-momentum loss after arrival on the ZAMS was gained from Doppler mapping of prominences with high-resolution optical spectroscopy (e.g. Collier Cameron 1996).

Additional support for an observational approach comes from the prediction of increased flare activity due to the effects of an orbiting planet (Cuntz et al. 2000). Or, the other way around, could flare activity be an indicator for the existence of a close planet? A search for such a correlation is clearly possible from the *Eddington* data.

Flares and (eruptive) prominences are complex and highly dynamic physical processes driven and controlled by stellar surface magnetic fields. Stellar flares on late-type stars can free a total energy of at least $10^{35}$ erg at the flare location, i.e. 100 000 times that of a strong solar flare while stellar prominences can reach out several stellar radii and are directly observable when they obscure the chromospheric and photospheric Hα light. These prominences could add an additional heating source for close (Vulcan) planets besides the host star’s UV radiation field.

7. Modelling of monochromatic light curves

Previous work by numerous authors has shown that broadband light curves of spotted, late-type stars can undergo changes on timescales ranging from days to years and are the most sensitive, and yet most easily accessible, indicator of spot activity. However, when combining data from several consecutive rotation cycles into a single light curve one usually cancels out the short-term variations. Therefore, long and uninterrupted light curves with good sampling would be needed to study the time dependence of...
the spot activity. That is why ground-based APTs (automatic photoelectric telescopes) are so well suited for stellar activity monitoring.

Nevertheless, there still is daytime every 12 hours and there still is "lousy" weather which leaves gaps in the data that may even prevent to reach the basic scientific goal. Clearly, we need to go into space for further significant improvements.

Fig. 7 shows two examples of light-curve simulations of a single solar-type star with a 17-day rotation period on the equator and a continuous observational coverage of 170 days (a ground-based "observing season"). The light curve in the left panel is for a star with two equally sized spots, one on the equator and one at a latitude of 60°. The differential (surface) rotation parameter $\alpha \approx \Omega_{\text{pole}}/\Omega_{\text{equator}}$ ($\Omega_{\text{pole}} \approx 0.2$) was set to 0.1, which means that the high-latitude spot’s angular velocity is approximately half that of the equatorial spot. The simulation starts with both spots at the same longitude. The right panel in Fig. 7 adds more complexity to the simulation. We start with two large equatorial spots, one on both sides of the star, and implement a surface meridional-flow law that adds a velocity component from the equator toward the poles. The spots on the equator break up into equal pieces and drift toward the respective poles. A solar-type differential rotation law with $\alpha = 0.05$ presets the angular velocity at each latitude during the drift to the poles. The resulting light curve (full line in Fig. 7b) is thus quite complex and includes a period increase due to the latitude drift. The dotted line in this figure is the light curve without differential rotation.

Finally, Fig. 8 shows a real application of such timeseries photometric spot modelling. This was published quite a while ago by Strassmeier & Bopp (1992) but remains to be a good example (but see more recent papers by the Konkoly group, e.g. Olah et al. 1999). Without going into the details, we deduced spot changes from one rotation to the next and even witnessed the formation of a new spot (or spot group). Continuing such a data set would allow, e.g., to establish a scaling law between spot lifetime and spot size, as for the Sun, and thus provide some quantitative input for solar and stellar MHD spot models.

Many authors have investigated the mathematic uniqueness of a solution from a fit to a single light curve, in one, two, or even three bandpasses (a recent brief review is given in Messina et al. 2001; for more details see e.g. Strassmeier & Bopp 1992, Olah et al. 2001 a.o.). In short, a single one-bandpass light curve contains an unrecoverable ambiguity between (relative) spot area and spot temperature. A minimum of one color is needed to constrain $\Delta T$ (photosphere minus spot temperature). A zero point in one bandpass is needed to constrain absolute spot area, and zero points of two bandpasses are needed to get absolute spot temperatures.

If zero point(s) are not known (or are too uncertain), a minimum of two colors from different parts of the spectrum is needed to decide between cool vs. hot spots (e.g., $U - B, V - I$). The optimum solution (within the mathematical approach adopted) is obtained when multi-color
stellar or \(UBVR_I\) photometry is applied throughout a rotational cycle of a star.

As of the time of the present meeting, \textit{Eddington} is foreseen to obtain white light photometry in order to reach maximum \(S/N\) for the shortest possible integration time. This is of course important to cover the high-frequency Fourier domain for the seismology targets as well as to reach very deep in case of the planet-transit search. On the other hand, it prevents any physical modelling for additional science in the field of stellar activity. What can be done very excellently though is geometric modelling of time-series data as outlined above. It would require additional ground-based, multi-color, photometric observations to determine average color indices along with spectroscopic observations in order to determine the basic astrophysical parameters and evolutionary status of the \textit{Eddington} activity targets. Only then can the \textit{Eddington} data be interpreted within the physical realism of the solar-stellar connection.

![Figure 9. The STELLA observatory of the AIP (under construction). It hosts a 1.2 m robotic telescope for high resolution Echelle spectroscopy and a similar telescope for CCD and PMT photometry.](image)

8. \textbf{GROUND-BASED SUPPORT OBSERVATIONS}

Fig. 9 introduces the STELLA telescope (STELLA stands for “stellar activity”). It will be a 1.2m robotic telescope at the Teide Observatory on Tenerife that feeds a bench-mounted echelle spectrograph with a set of 50 and 100 \(\mu\)m fibres and provides resolutions of up to 50,000 with a 1 arcsec slit. The spectrograph is a FEROS-like design located in a separated temperature-controlled room within the STELLA building to guarantee long-term stability. The building will have a roll-off roof capable of hosting two telescopes. First light for STELLA-1 is planned for fall 2002. STELLA-2 will be a photometric telescope and first light is not expected before 2004. More details are provided at \url{http://www.aip.de/stella}. STELLA is an ideally suited facility for ground-based support of the \textit{Eddington} mission.

A facility that has been in operation now for almost two decades is Fairborn Observatory. Fig. 10 shows the robotic telescope farm at the new Fairborn Observatory in southern Arizona. Currently, Fairborn hosts 12 APTs (automatic photoelectric telescopes) from a half a dozen institutions, several of them dedicated to monitoring stellar activity, including our Wolfgang-Amadeus telescopes\(^3\). Furthermore, Tennessee State University is building a 2 m robotic telescope there, which should see first light very soon\(^4\) and which will be also used for stellar activity work.

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\textbf{REFERENCES}


\(^{3}\) See \url{http://www.aip.de/groups/activity/KPT} and follow further links there.

\(^{4}\) \url{http://schwab.tsuniv.edu/apt.html}