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Time series photometry and starspot properties

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Abstract. Systematic efforts of monitoring starspots from the middle of the XXth century, and the results obtained from the datasets, are summarized with special focus on the observations made by automated telescopes. Multicolour photometry shows correlations between colour indices and brightness, indicating spotted regions with different average temperatures originating from spots and faculae. Long-term monitoring of spotted stars reveals variability on different timescales.

On the rotational timescale new spot appearances and starspot proper motions are followed from continuous changes of light curves during subsequent rotations. Sudden interchange of the more and less active hemispheres on the stellar surfaces is the so called flip-flop phenomenon. The existence and strength of the differential rotation is seen from the rotational signals of spots being at different stellar latitudes.

Long datasets, with only short, annual interruptions, shed light on the nature of stellar activity cycles and multiple cycles. The systematic and/or random changes of the spot cycle lengths are discovered and described using various time-frequency analysis tools. Positions and sizes of spotted regions on stellar surfaces are calculated from photometric data by various softwares. From spot positions derived for decades, active longitudes on the stellar surfaces are found, which, in case of synchronized eclipsing binaries can be well positioned in the orbital frame, with respect to, and affected by, the companion stars.

Keywords. Stars: activity, stars: spots, stars: rotation, stars: late-type

1. Introduction

Nearly a century ago, at about the same time when the magnetic field of the sunspots were first measured, a short note of Eberhard & Schwarzschild (1913) called the attention to the similarity of the solar activity and the newly measured stellar feature in the CaII H&K lines: *The same kind of eruptive activity that appears in sun-spots, flocculi and prominences, we probably also have to deal with in Arcturus and Aldebaran and in a very greatly magnified scale in σ Geminorum.* In the same time photographic monitoring of certain parts of the sky commenced in a few observatory. Later these plates were used to extend the databases of active stars to check their long term behaviour. Starting with data from the Harvard plate collection by Phillips & Hartmann (1978) (big dots and bars until 1970) to the most recent results of Messina (2008) (bars after 1990) - and dozens of published data in between (small dots) - a more than century long light curve of BY Dra is presented in Fig. 1. This figure shows clearly how short is a century for studying long term variations in stellar activity. However, results based on time series photometric data emerge as the databases are growing in time. These results are reviewed in the followings.

The origin of the photometric variability of active stars is due to the work of magnetic dynamos in their interiors. The description of the dynamo processes and how spots are formed is far beyond the possibility of this review, however, the reader finds ample papers to read more about the dynamo mechanism within this Proceedings.

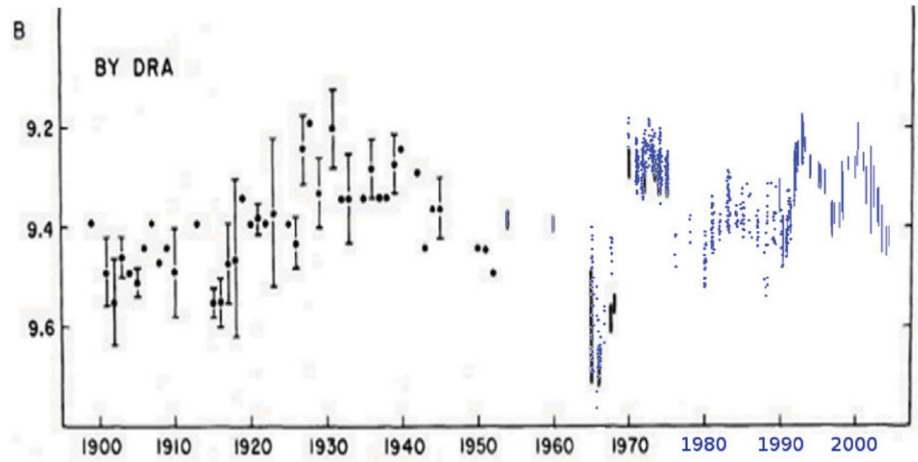

Figure 1. Long term light variation of BY Dra over a century, from photographic and photometric data.

2. Telescopes, filters and tools

Photometric observations of active stars began in the mid 1960's in different observatories after discovering the "rotational modulation" of the already known and studied flare stars. The systematic studying (day-by-day observations) of stellar activity needed cheap and dedicated instruments. Since the manpower is the biggest cost in operating a small telescope suitable for measuring the relatively bright (4-10 mag.) stars, fully automated telescopes were built for the task. The first one was the Phoenix 25cm APT which served the community for 23 years, its program consisted of several different types of variable stars. Dedicated mostly to active star research the Catania APT operated from 1992 till the recent years (see e.g. Strassmeier *et al.* (1997b)). At present, three APTs are gathering the data on active stars for more than a decade: the Wolfgang-Amadeus Vienna twin APT Strassmeier *et al.* (1997a) and APT of the Four-College Consortium. Rodonò *et al.* (2004) a few years ago summarized the use of robotic telescopes in stellar activity; the interested reader finds useful references in this paper. Space observatories (CoRoT, Kepler) are also gathering data on active stars in a much higher magnitude range than from the Earth, giving uninterrupted and very high quality data for hundreds of objects. The planned durations of these projects are, unfortunately, below the time scale of spot cycle variations.

The filter sets were different in the APTs of long run. The Phoenix 25cm and the Catania APT had Johnson UBV, while now Wolfgang (T6) has $uvby$, Amadeus (T7) has $V(RI)_C$, and the Four-College APT has $uvby$, $V(RI)_C$, TiO and Hα filter sets. This means, that the longest databases to study activity cycles are available only in one passband, i.e., in V combined with the very similar y. The datasets in the different colour indices $(B-V)$, $(V-I)_C$ are generally shorter and even less is the case when both blue and red colour index time series observations exist for one star. Even worse is the situation with the space observatories: at present they do not observe in any established colour system.

Rotational and cycle periods from the photometric data are searched for by different period finding algorithms. The most commonly applied one-dimensional Fourier transform however, is not well suited to find periods of rotational modulations because of the differential rotation which can be strong - although can give a hint about it. Fourier

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analysis may fail for double humped light curves; these cases Lafler-Kinman type procedure can help. Various time-frequency algorithms exist and are used for studying longer-term variations: for a summary see Kolláth & Oláh (2009).

Attempts for modeling starspot positions and spot temperatures from photometric data commenced together with the start of the systematic observations of active stars. Two other methods and approaches are used, developed by different authors and groups.

Starspots, as the sunspots, emerge, stay for some time and decay. Since our knowledge at present is limited to indirect spot maps with very low resolution, we do not know if the spots are uniform dark, cool regions, or are combinations of cool and hot areas of different temperatures. Photometric measurements in different colours suggest the second possibility. Active stars are redder when fainter in $V - I_C$ and usually also in $B - V$ and $U - B$, but not always, see Messina (2008) for the most complete study in UBV. From the amplitude of the colour index curve average temperature of the spotted region relative to the surrounding photosphere can be determined. These "spot temperatures" are warmer than those on the Sun and show variability on different timescales, therefore are more resembling to the active nests on the Sun than to the individual sunspots.

3. Starspot changes on rotational timescale

Systematic monitoring of active stars show that the measured light variations caused by spots on the rotating stellar surfaces show continuous, and sometimes sudden, changes. The origin of these observed changes are reflections of the changes in the spots' properties: positions, temperature, lifetime.

Fig. 2 shows the time-frequency behaviour of CoRoT-Exo-2a with the planet transits and starport changes. It is well seen that the signal of the transit is (naturally) very regular and several harmonics are present. Together with this regular pattern the rotational signal of the active (host) star is seen, with slow changes of the period around 4.5 days, due to the differential rotation. A temporary period doubling is also seen indicating two close periods by spots at different latitudes. Longer, slowly varying periods of about 28-29 and around 86 days are also seen. All periodicities are discussed in detail by Lanza *et al.* (2009). Fig. 2 shows the power of the time-frequency analysis in giving a first estimate of the observed periodic signals and a first guess about their origin.

3.1. *Differential rotation - quiet spot patterns*

On the stellar surfaces active regions with starspots are found at different latitudes, rotating with different periods. The signal of the differential rotation is usually present in the observed light curves appearing as several close periods in period search results. The bunch of resulting periods give only a guess about the existence and a limit of the strength of the differential rotation. For short period active stars, when enough data is available, seasonal mean rotational periods can be obtained. However, the errors should be calculated with care to see the reliability of the differences, if any. Only in lucky cases and with the help of corresponding Doppler imaging to the photometry is possible to derive the the strength and the sign (solar type or opposite) of the differential rotation. One good example is given by Oláh *et al.* (2003) for the active giant star UZ Lib, where a long-lasting equatorial and high latitude spotted regions were identified in Doppler images and their rotational periods were found from photometry.

Until recently the most straightforward, direct approach to derive differential rotation from photometric data failed, since the photometric precision (a few thousandths of a

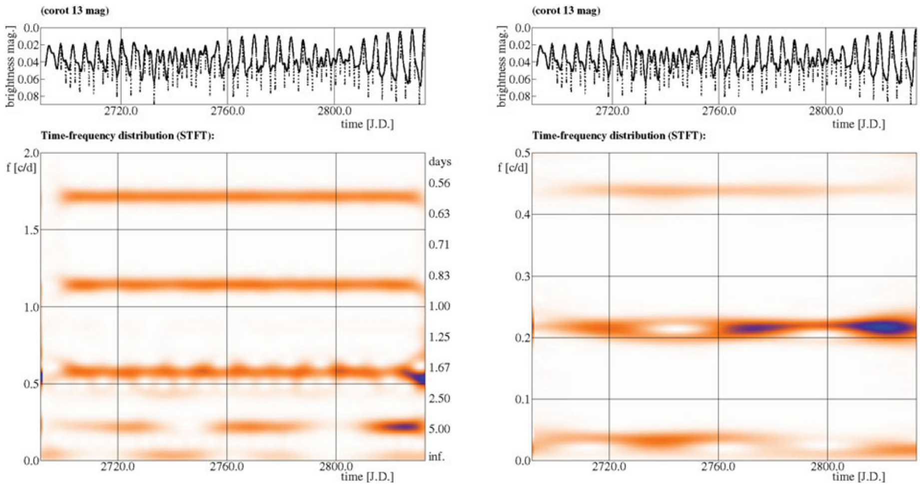

Figure 2. Analysis of the original dataset of CoRoT-Exo-2a (with some pre-filtering only). Left: time-frequency diagram from 0.5 days, right: the same from 2 days. On the left the periodicity of the planet transit (1.743 days) is seen with some cross-talk with the half of the star's rotational period. On the right only the signals from the star (rotational period of 4.5 days, its half and long periods) are seen.

magnitude) was too low to derive spot latitudes, which is strongly related to the inclination of the star and is affected by the limb darkening at different latitudes. However, the present, very high precision, uninterrupted datasets acquired from satellites make possible to get this important parameter directly from the light curves. Walker *et al.* (2007) derived accurate differential rotation parameter for κ^1 Cet from photometric data obtained by the MOST satellite.

3.2. *Spot emergence, decay and proper motion - fast changing spot patterns*

Spot emergences - sudden change in the light curve - and decays have already been measured for several active stars during their continuous monitoring. The effect is best seen in uninterrupted, satellite datasets. The period doubling shown in the time-frequency plot on Fig. 2 and the corresponding sudden change of the light curve suggests a restructuring of the spots on the stellar surface, possibly by new spot emergence(s) at different latitudes. The two periods reflect the differential rotation but additional spot proper motion (typical for newly emerged spots) could change the rotational period of the spots. In the same dataset traces of spot decay and emergence of new spots are also found by Lanza *et al.* (2009)). It is interesting to compare the results originating from two totally different methods using on the same dataset.

4. Long term variability of starspots

The behaviour of the spottedness of stars is particularly interesting on the decadal timescale. This includes the changes (or constancy) in position (longitude), size and temperature of the starspots. Only APTs using *the same instrument* with well-defined filter sets are able to follow the temperature and the closely related size variations of the starspots.

4.1. *Active longitudes*

It is well known that most photometric light curves of active stars can be depicted by two active regions, the so-called active longitudes. Spots may appear on other parts of the stars, more evenly distributed or in the polar region from where they do not cause rotational modulation, but their changes affect the overall brightness of the stars on longer timescale. The information content of the photometric data, even if multicolour, is limited in reconstructing the spot positions, only the longitudes of the major spot groups can be derived safely. However, comparing Doppler images with contemporaneous photometry the existence of active longitudes are proved in several cases (see e.g. the latest: Frasca *et al.* (2010)), high latitude or polar spots are also found as common feature on Doppler maps.

The presence of active longitudes observed in many close binaries can be explained by the tidal effect which help the erupting flux tubes to cluster around two longitudes on the opposite hemispheres of a star, synchronized to the orbital motion, see Holzwarth & Schüssler (2003) for details. One example (among many) is the RS CVn binary RT Lac (G5:+G9IV) studied in detail by Lanza *et al.* (2002). Both components of this binary are active and show enhanced spottedness at the substellar points and on their opposite sides.

4.2. *Flip-flop phenomenon*

Time series photometry shows, that the dominance of the activity can change between two active longitudes, which are usually separated by about 180°. This effect is called as flip-flop, and the elapsed time between two such change is the flip-flop period. Several active stars show this feature, a recent summary is found in Korhonen & Järvinen (2007). In lucky cases the flip-flop, i.e., the interchange between the more active hemisphere of a star is directly observed, as in the case of FK Com by Oláh *et al.* (2006). The long term homogeneous datasets are of vital importance in studying this strange behavior of magnetic activity. For theoretical background of the phenomenon see Korhonen & Elstner (2005) and the references in its Introduction.

4.3. *Activity cycles*

An important - maybe the most important - result of the time-series observations is the detection and tracking the magnetic cycles of different types of active stars. This study needs the most expensive factor of an astronomical research: *time*. Only one smooth sine-like change in the overall brightness of a star during a few (a dozen) years cannot be called cycle, which, by meaning, is a repetitive pattern, with at least a characteristic timescale (see the variability of BY Dra for more than 100 years in Fig. 1). The correct timescales of the activity cycles is of fundamental importance as an observational basis of dynamo modeling. Studying cyclic behaviour of different stars may help to generalize this feature, which then helps us to better understand the behaviour of our Sun, and that is of vital importance, by its full meaning.

Active stars are found in the galactic field as well as in young open clusters. An important study yet to be done, is to monitor the time behaviour of activity of stars in clusters which would allow to compare the cyclic (and also rotational) behaviour of coeval stars. This way we get rid of the age factor and most of the composition difference, so we can concentrate on the evolutionary effect, which depend on the mass of the stars. A pioneering long-term study is being done on stars in Pleiades by Milingo *et al.* (2011).

On Fig. 3, left, the time behaviour of the activity cycles of EI Eri is plotted based on 28 years of monitoring. In a way this picture is typical: most studied active stars show

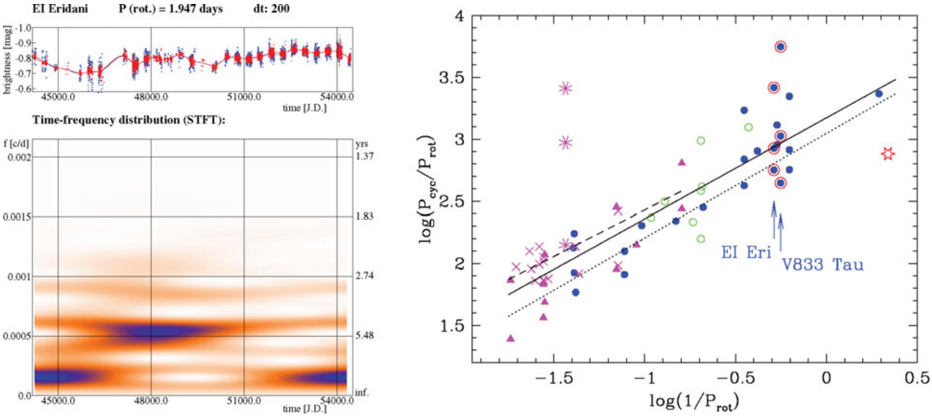

Figure 3. Left: Time-frequency plot of EI Eri, showing multiple and changing cycles. Right: the relation between rotational and cycle periods. The solid line shows the relation for all derived cycles except the long cycle of the Sun (stars), dashed line is from Baliunas *et al.* (1996), dotted line is the fit to the shortest cycles.

multiple and changing cycles, like this example. Dwarfs and giants, singles and binaries, young and evolved stars are among the studied 20 objects by Oláh *et al.* (2003), and all share the same characteristics. The right side of Fig. 3 shows the cycle length - rotational period relation ($P_{\rm cyc}/P_{\rm rot}$) originally given by Baliunas *et al.* (1996) derived from the Wilson sample: *"Theoretical considerations suggest that the ratio is the observational equivalent of the stellar dynamo number, D."*.

The two marked stars on Fig. 3, right, EI Eri and V833 Tau have very similar rotational periods of 1.95 and 1.79 days, respectively, but are much different in all physical parameters, EI Eri is a subgiant and is 10 times older than the mid-K dwarf V833 Tau. Yet, their short cycles are similar, but not the long ones. Whether it is due to the limited length of datasets remains to be seen by my successors, *in a century or more.*

5. Acknowledgements

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Discussion

Dupree: I just want to make a comment that they are now digitizing the Harvard plate stacks, and there have been several papers published on variable stars, variable giants, and other anomalies for 100 years of photometry. So go to it. There's a lot there.

Oláh: Thank you.

Strassmeier: Well, I couldn't agree with you more, Katalin, as you probably know; but I do disagree on one point. You mentioned that, if the light curve gets precise enough, you can retrieve latitudes. I think this is wrong. You can have infinite precision light curves. You're not going to get latitude out of a one-dimensional light curve. It's, I think, mathematically impossible. If you assume a circle, a model, per se – if you assume that, then you get the latitude out from high-precision light curves if you assume square spots, you also get a latitude curve out. If you assume triangle spot, you also get a latitude out. So it's model dependent. Then, yes, but not in general if you let spot areas completely free, pixelize it, as we do in inversion, then you do not get a latitude out.

Oláh: You are absolutely right, and I suggest to devote a special conference to the question. Why is it fair to suppose a circular spot? Because we see circular spots on the Sun. Circular spot is an assumption, and I fully agree with what you say when you suspect other spot shapes.

Kővári: *To Strassmeier* This is not fully true because once we have limb darkening, we'll have latitudinal information, too.

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