STELLAR PHOTOMETRY WITH A WHOLE-EARTH ROBOTIC TELESCOPE

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ABSTRACT. This paper addresses the potential of a global network of robotic telescopes for starspot research. Observations of rotational modulation of the continuum brightness of late-type stars indicate the presence of very inhomogeneous surface temperature distributions changing with timescales from days to years. We are currently using two (but soon four) APTs at sites in the U.S. and Italy and manual observations in China to monitor short-term light curve variations of a sample of four active stars (IN Com, FK Com, EI Eri, V833 Tau) for two years. I discuss three other stars (VY Ari, HR 7275, HU Vir) where time-series photometry was used recently to trace the evolution of spotted regions.

A WHOLE-EARTH ROBOTIC TELESCOPE?

By “Whole Earth” is meant several fully automatic photometric telescopes located at different geographic longitudes around the globe (Fig. 1). Not only are the telescopes automatic, but the observatories themselves are automatic. A site-control computer monitors weather sensors, operates the roof, and provides a daily report to the observatory staff, who are located hundreds of kilometers away. Currently, there are only three sites making routine photometric observations of active stars with an APT\(^1\) (on Mt. Hopkins near Tucson, Arizona, at Villanova University in Pennsylvania, and one near Catania, Italy) but in late 1993 two more sites will be operational (on Mt. Wilson, California and in Korea). We are already using the existing APTs for dedicated observing campaigns and proposed to include the new robotic telescopes and also plan to purchase an Autoscope, Inc. 0.8-m system to be operated in Australia. Currently, additional (manual) observations are carried out at the Matra mountain station of the Konkoly Observatory, Hungary (1-m telescope equipped with an \(UBVRI\) photometer and operated by Dr. Katalin Olah) and at the Beijing Observatory, China (0.6-m telescope operated by Dr. J. Shi-Yang). A first run of this semigNAT\(^2\) in April 1993 included the Fairborn and the Italian APTs and manual observations in Hungary, China, and at McDonalds Observatory in Texas. The next upcoming runs (November 1993, April 1994, November 1994) will additionally include the APTs in Korea and at Villanova. The November campaigns concentrate on EI Eri and V833 Tau and the April campaigns on IN Com and FK Com. Each campaign lasts for three continuous weeks. In the first observing

\(^1\)Automatic Photoelectric Telescope
\(^2\)Global Network of Automatic Telescopes

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run it turned out that data handling is not a straightforward problem so I am not yet able to present preliminary results from the April 1993 campaign. Instead I would like to present some APT results on three other stars (two of them not published yet) that show significant short-term light curve variations and I will also briefly outline the analysis technique.

**STARSPOT PHOTOMETRY: SCIENTIFIC GOALS**

A significant part of the past and recent progress in the study of starspot on late-type stars has come from the analysis of broad-band light curves (for recent reviews on starspot photometry see, e.g. Hall 1991, Eaton 1992, Strassmeier 1992, Guinan & Giménez 1993). The “starspot hypothesis” is that a spotted star’s periodic light variation results from an inhomogeneous surface temperature distribution and is modulated with the stellar rotational period. Long-term variations of light curves might tell us the existence and length of a spot cycle similar to the solar 11-year cycle.

A further step in understanding spot activity in RS CVn-type systems is the
Figure 2: Rapid light curve variations of the RS CVn binary El Eri in late 1988 as deduced from the IUE/FES readings. Two consecutive rotational cycles have been covered. The crosses are simultaneous ground-based data points from an APT.

continuous, uninterrupted observations of such systems at all timescales: long-term (years) and short-term (days). Since a spotted star’s light curve is the most sensitive signature for the longitude, size, and temperature of the spots, it is also easily obtained with even a very small telescope. Short-term monitoring over several consecutive rotational cycles would provide the lower limit for spot lifetimes, a quantity which only just recently became important: time resolved Doppler images of the spotted RS CVn binary El Eri showed rapidly changing equatorial spots (timescales of one week) and a steady polar spot (timescales of years) which, however, changes its shape also very rapidly (Strassmeier 1990, Strassmeier et al. 1991); this has been confirmed by an independent series of Doppler images by Hatzes & Vogt (1992). During a campaign of multi-wavelength observations of El Eri in late 1988 we observed a smooth change of the visual light curve from one rotation cycle to the next (Neff et al. 1993) using the Fine Error Sensor onboard the IUE satellite (Fig. 2). This result is still to be confirmed but, if correct and not an instrumental effect, poses a serious problem for any observing campaign based on data accumulation with timescales greater than one rotation cycle. Our GNAT observations are primarily aimed at the detection of these short timescale variations and their interpretation. Figure 2 shows the calibrated IUE/FES light curve of El Eri. Note that the rotation period of El Eri is close to a multiple of a day (1.945 days) and the light curve in Fig. 2 could not have been observed from a single ground-based site but only from space or from a global network.

THE ANALYSIS TECHNIQUE: TIME-SERIES SPOT MODELING

To model the GNAT observations we will make use of a multiple-spot computer program developed by myself. This program has been modified to run also in
Figure 3: Results of fitting the 1988/89 (upper left panel) and the 1989/90 time series (lower left panel) of VY Ari. The dots in the left panels are the APT observations and the full line is the model fit. The straight dotted line represents the $V$ brightness from 1986. The small panels are the model parameters from top to bottom, spot latitude, spot longitude, and spot area, where the different symbols denote different spots. The right panel visualizes the results.

time domain and can now be used to follow the light curve of a spotted star with intrinsically variable (time-dependent) spot parameters. This is exactly the kind of tool we need to analyze long time series of light curves as produced by the new generation automatic photoelectric telescopes.

Basically we apply a least-squares, trial-and-error, algorithm to several consecutive light curves of a rotating star within a given parameter space. Every point in the theoretical light curve is computed from a disk integration of a model star with a simple Planckian energy distribution to convert effective temperature to flux. Estimates for the surface temperature are obtained from the variations of $V - I$ color curves and are adopted to be constant throughout the rest of the $V$ observations. Time-dependence is introduced for the other spot parameters with a solar-type differential rotation law $\Omega = \Omega_0 + \Omega_2 \sin^2 \theta$, as well as cyclic behavior of the spot latitude and area in analogy to the solar 11-year cycle.

Modern computers then allow to search through the entire multi-dimensional parameter space, i.e. spot longitude, latitude, area, differential rotation $\Omega_2$, ...
cycle length and cycle amplitude, and find all physically reasonable solutions. While we cannot claim that the spot solutions of the individual light curves are mathematically unique, we are able to separate periodic effects – like differential rotation or waxing and waning of particular spots – from stochastic effects that are presumably unrelated to a magnetic cycle.

**RECENT RESULTS ON LONG-PERIOD STARS**

**VY Ari = HD 17433**

The results for this star are already published by Strassmeier & Bopp (1992). Here I just give a short summary. VY Arietis = HD 17433 is a K3-4IV component in a 13.2-day single-lined spectroscopic binary (Bopp et al. 1989). It’s mean rotational period, however, is 16.67 days and VY Ari thus represents the case of an asynchronously rotating stellar component. Figure 3 shows the APT V-band photometry for the observing seasons 1988/89 and 1989/90 and our spot-model fits. The small panels in Fig. 3 present the results. The change of the V amplitude from 0.4 mag to 0.2 mag within the observing season 1988/89 required the total spotted area to vary between 10 and 15% of the stellar surface. To account for the change of the mean light level of up to 0.2 mag between 1986 and 1991, we chose a polar spot of variable size, but same temperature difference that was derived from the modulation of the V – I color curve (i.e. ΔT ≈ 1200 K).

The light curve behavior in the first season (1988/89) is dominated by a monotonic decrease of the two big spots at longitudes ≈ 40° and 300°, respectively, by about a factor of two. Additionally, we witnessed the gradual appearance and disappearance of a third, smaller spot at a longitude of 130±10°. A similar-sized spot has been also seen at the same longitude four years earlier, as well as a larger spot covering the same longitude region as the two big spots in 1989/90. Though not conclusive, this is evidence for the existence of “active” longitudes on VY Ari.

In the second season (1989/90) the one big spot at longitude 40° vanished completely, but a new spot emerged at l = 90° well within one stellar rotation cycle, i.e. 16 days, and perhaps even within a few days. At the end of the season this spot reached the same size as the other two spots and, at that time, three spots of approximately equal size were present and the amplitude was down to 0.1 mag. The spots between 180 and 360° showed a significant longitudinal migration (Fig. 3, right panel); both spots first migrate about 30° towards longer longitudes until a standoff at cycle 27 which is followed by a retrograde migration back to the original position. Interestingly, the third spot at l = 90° remained fixed at its position.

**V1762 Cyg = HR 7275**

HR 7275 is a 28.6-day spectroscopic binary with a K1III-IV primary and an unseen secondary component. Representative light curves and the results of our modeling are shown in Fig. 4. Altogether we have 15 consecutive years of pho-
Figure 4: Seasonal $V$-band light curves of HR 7275 for the years 1988 through 1992 and our spot-modeling fits. The left panels show the data versus heliocentric Julian date (2,440,000+) and the right panels are the phased light curves with the orbital period. The full line in each Julian-date panel is the fit with a spot model as explained in the text.

The photometry including APT data from 1983 on. Each observing season was treated as a separate data set and the modeling is done in time steps of 0.4 days, i.e. 72 steps per stellar rotation.

Our data showed HR 7275 at its brightest level with a peak magnitude of $V_{\text{unsp}} = 5.736 \pm 0.005$ mag at the end of 1981, which we assume to be the unsptotted brightness of the star. Knowledge of the true unsptotted brightness is essential for light curve modeling because it controls the spot area and temperature. Again we must assume some light dimming mechanism that does not contribute to the rotational modulation and we adopt a polar spot of variable size to adjust the different seasonal light curve maxima. This is essentially a techniquality because we could have also adopted a variable background spottedness (cf. Eaton & Hall 1979) but the polar-spot picture is supported from Doppler-imaging results of other RS CVn binaries of similar spectral type (cf. Vogt 1988, Strassmeier et al. 1991). For example, Rodonó et al. (1986) assumed all the light loss is due to two spots and got high spot latitudes as a result. To the contrary, Dorren & Guinan (1990) argued that, in the case of the RS CVn binary V711 Tau, a variable facular contribution to its continuum brightness is the cause for the long-term variations. Although the observational evidence for a relation
between continuum brightness variations and magnetic activity cycles is strong, but probably not yet conclusive, its underlying physical reason still remains to be determined.

The only VRI data of HR 7275 are the Kitt Peak data of Poe & Eaton (1985). These authors already performed a spot model analysis on these data and found two high-latitude spots covering $\approx 9\%$ of the surface and being 1200 K cooler than the photosphere. However, their light curve fit produced a peak magnitude brighter than the observed one by 0.07 mag. The reason for this discrepancy was that their adopted unspotted brightness of 5.84 was too faint by 0.1 mag and, as was pointed out by the authors, made the derived spot temperature probably too cool. The observed $V - I$ amplitude of $\approx 0.07$ mag at around phase 0.9 is best reproduced with spots having a temperature difference (photosphere minus spot) of $800\pm 200$ K, instead of the 1200 K obtained by Poe & Eaton. We adopted a stellar surface temperature of 4820 K from the spectral type – temperature calibration of Bell & Gustafsson (1989) and an inclination of the rotation axis of 70°. The relatively high inclination was adopted on the basis that the unseen secondary companion is a main sequence star and that no eclipses are observed (Eker 1989).

Scharlemann (1982) showed that the forces in a binary system, that act to achieve synchronism between surface rotation and orbital revolution, are not strong enough to suppress differential (surface) rotation. These calculations supported the suggestions of Hall (1972) that there is a co-rotating latitude at which the rotation is synchronized to the orbital motion. Thus we can interpret a particular photometric period of a spotted star as the rotation period at the latitude of the spot that causes the light modulations. If we assume solar-like differential rotation, i.e. the polar regions rotate slower than the equatorial regions, then a photometric period longer than the orbital period would indicate a spot latitude above the co-rotation latitude and vice versa. The range of photometric periods on HR 7275 spans from 8% slower than $P_{\text{orb}}$ in 1983 to 7% faster than $P_{\text{orb}}$ in 1982, with a mean value of 28.241±1.037 days between 1978 and 1992, i.e., on average 1.2% slower than the orbital period. Obviously, the rotation of HR 7275 is synchronized to the orbital revolution but the spots reside above and below the co-rotation latitude.

**HU Vir = HD 106225**

HU Virgo is a K0IV component in a 10.4-day single-lined spectroscopic binary system. The star shows very strong Ca II H and K emission lines and a complicated and variable H\textalpha line profile (Strassmeier 1993).

The spot distribution in 1991 remained fairly stable. Obviously, the lifetime of the two big spots (spot A and B) was greater than the time span of our observations, i.e. more than approximately six months. Only at the very end of the time series (Fig. 5) do we see a major change in the light curve shape, which can be accounted for with the appearance of a third spot (spot C) within one half of a stellar rotation. Its determined position is not as precise as for
Figure 5: Time-series photometry of HU Virgo from the entire 1991 observing season. Dots are the observations from this work and crosses are from Hall & Henry (1992). The full line is a least-squares fit with a time-dependent spot model. The horizontal bars indicate the times of spectroscopic observations at NSO and KPNO. The best fit was achieved with two major spots slightly variable in size and migration rates. At around HJD 2,448,400 a third spot appeared at a longitude of $\approx 130^\circ$.

Spot A and B because of its small size. A comparison with our solution from 1987 shows the primary minimum at about the same phase as in 1991 ($\approx 0.1$) while Fekel et al. 's (1984) data from 1982 showed the primary minimum at phase $\approx 0.4$ indicating a significant change of the spot distribution between 1982 and 1987. Sporadic areal changes of spots A and B by a few percent were present throughout the observing season 1991 (Fig. 6) and indicate that the small-scale spot distribution, which is likely unrelated to a long-term magnetic cycle, is changing all the time. The total spotted area also varied, but only marginally, from 9.5% to 11.3% between January and July 1991.

The most obvious feature from Fig. 6, however, is the longitudinal migration of spots A and B. Linear least-squares solutions for the change of their longitudinal positions with respect to the observer's frame (lower panel of Fig. 6) imply daily migration rates for spot A and B of $-0.16 \pm 0.02^\circ$/day and $+0.10 \pm 0.02^\circ$/day, respectively. Their respective rotation periods, determined from $P_{\text{migr}}^{-1} = P_{\text{phm}}^{-1} - P_{\text{orb}}^{-1}$, are 10.436$\pm$0.008 days and 10.357$\pm$0.010 days and differ by $(P_{\text{phm}} - P_{\text{orb}})/P_{\text{orb}} = +0.0047 \pm 0.0007$ and $-0.0029 \pm 0.0009$ from the orbital period. Thus, the latitudinal regions at spot A rotate slower than the orbital period and the latitudes where spot B is located rotate faster than the orbital period. Solar-like differential rotation would make the photometric (rotation) period shorter if a spot is near the equator and longer if it is closer to the pole. However, the situation appears reversed if the differential rotation parameter is negative, i.e. when the polar regions rotate faster than the equatorial regions. The latter has been found to be the case on the RS CVn binary UX Ari (Vogt & Hatzes 1991). The different signs of $\Delta P/P$ for the two persistent spots...
Figure 6: Results from modeling the 1991 photometry of HU Virgo. The arrows indicate the respective values for the three spots in 1987. The full lines in the lower panel are least-squares fits to the spot migration. These migration rates are consistent with differential surface rotation ten times less extreme than on the Sun. Note the erratic, but smooth, spot area changes (upper panel) which are likely unrelated to a spot cycle. The total spotted area varied between 9.5 % and 11.3 %.

on HD 106225 suggest that they are located at different latitudes, one above the co-rotation latitude the other below it. Because the results in Fig. 6 can not tell us the sign of the differential rotation parameter on HD 106225 we can not say which of the two spots is below or above the co-rotation latitude. However, the amount of differential rotation can be estimated from the difference of the observed spot periods \((P_{\text{spotA}} - P_{\text{spotB}})/P_{\text{orb}} = 0.0076 \pm 0.0017\) and, if we assume a total range of latitudes of 45°, this would be differential rotation 15 times less extreme than the solar case.

We now identify spots A and B with two polar spot appendages seen in our contemporaneous Doppler maps from April 1991 (not shown). This provides a good estimate for their mean latitudes of approximately +40° and +60°, respectively. It is plausible to assume that the previously measured photometric periods for spot A and spot B are the stellar rotation periods at a latitude of +40° and +60°, respectively. Thus, the 60° latitudinal zone rotates faster than the zone at 40°. Formally, we may express our rotation measurements from two latitudinal zones in a solar-type differential rotation law of the form \(\Omega = \Omega_0 + \Omega_1 \sin^2 \theta\) where, for the Sun, the coefficients \(\Omega_0 (=2\pi/P_{\text{equ}})\) and \(\Omega_1\) are determined to be 14.551 and -2.87 °/day, respectively using sunspots as tracers (Balthasar et al. 1986). For HD 106225 we obtain a preliminary differential rotation law of

\[
\Omega = 34.17 \pm 0.07 + 0.78^{+0.2}_{-0.1} \sin^2 \theta
\]  

(1)
where the standard deviation of coefficient $\Omega_1$ is mainly due to the uncertainty of the latitude of the polar appendages with respect to each other ($\approx 5^\circ$) and for coefficient $\Omega_2$ due to the uncertainty of the slope in Fig. 6. The differential rotation parameter, defined as

$$\alpha \equiv \frac{\Omega_{\text{equator}} - \Omega_{\theta=45^\circ}}{\Omega_{\text{equator}}}$$

is $-0.011$ and $+0.11$ for HD 106225 and the Sun, respectively. If we believe the latitudinal information content of our Doppler maps we tentatively conclude that, first, higher-latitude regions rotate faster than lower-latitude regions (opposite to what we see on the Sun) and, second, the difference of rotation periods between the latitudinal position of the two appendages and the equator is consistent with a differential rotation parameter 10 times smaller than for the Sun. Certainly, this remains tentative because it is based on period measures at just two stellar latitudes.

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