EDDINGTON AND STELLAR-ROTATION STUDIES: LIGHT CURVE ANALYSIS TOOLS AND GROUND-BASED FOLLOW-UP SPECTROSCOPY

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\section*{Abstract}

\textit{Eddington} will produce a data stream of light curves for some tens of thousands of stars. This means that a clever algorithm must predetermine what type of variability is expected for a particular target, and then suggest and apply the proper analysis tool. We investigate the feasibility of such an algorithm by comparing the chances of detecting the solar rotational period from the long-term Sun-as-a-star ACRIM data by means of Fourier and wavelet period-search techniques. We first create artificial data with a spot-modelling code that includes differential surface rotation, and then try to recover the rotation signal from the Fourier spectrum. Then, we present the example of the rapidly-rotating spotted star \textit{UZ Librae}, where ground-based time-series photometry obtained with automatic telescopes indeed revealed signal from a differentially rotating stellar surface. Finally, we discuss the urgent need for ground-based preparatory and follow-up spectroscopy and introduce our own support possibilities. We emphasise that all proposed joint \textit{Eddington}-support efforts, with our Spanish colleagues on the Canary islands and our Italian and American colleagues in Arizona, strongly suggest that the planet-finding field is in the northern hemisphere.

Key words: Stars: activity – Stars: photometry – Stars: rotation – Planets: exo-planets – analysis techniques

\section{1. Introduction}

Auxiliary science with \textit{Eddington} will touch almost any field in astronomy, from the brief optical afterglow of extragalactic gamma-ray bursts to the long-term cyclic light-curve variations of solar-type stars. Auxiliary science will also benefit from both primary science goals of the mission and vice versa. First, all the (expected) 20 or so asteroseismology fields (the "AS-fields") to be observed over the course of two years will contain a number of targets that are too faint for 1–100 ppm photometry but where even 1000 ppm rms would be a tremendous gain in precision and accuracy as compared to what is achievable from the ground. These auxiliary targets must be found and defined before each observation is started. The large defocusing for the asteroseismology fields (between 20 and 45 arcsec, see Catala 2003) limits the access to targets brighter than, say, \( V = 13 \) (and fainter than \( V = 6.5 \)), which is a serious limitation e.g. for M dwarfs. Secondly, the envisioned 3 yr monitoring of a single planet-finding field (the "PF-field") will provide light curves of tens of thousands of stars, predominantly G to M type main sequence stars, peaking in number at K type. It will contain many giants as well, although these are not desired from the planet-finding point of view (see Brown 2003). Clearly, the PF-field is where most of the auxiliary science will be done and, therefore, it is very important for the European auxiliary-science community where this field will be located (see also Piotto et al. 2003). In the present paper, we present the case for a field in the northern hemisphere, because ground-based spectroscopic follow-up as well as preparatory work may decide of the degree of success of \textit{Eddington}. This is a follow up to the paper we presented at the first \textit{Eddington} Workshop in Cordoba (Strassmeier 2002).

In the following we investigate the expected number and types of auxiliary-science targets by elaborating upon results from ground-based wide-field photometric imaging surveys (Sect. 2). We then proceed to period detection in time-series photometry, with an emphasis on stellar rotation, and especially differential surface rotation of spotted cool stars (Sect. 3). Finally, we discuss the importance of ground-based support and list possible contributions (Sect. 4).

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|}
\hline
Galactic latitude & F & G & K & M \\
\hline
5° & 100,000 & 100,000 & 100,000 & 10,000 \\
30° & 100 & 5000 & 10,000 & 5000 \\
\hline
\end{tabular}
\caption{Estimates of the expected numbers of stellar targets in the PF-field. Based on the power-law distribution functions presented by Horne (2009, 2003).}
\end{table}

\section{2. The observing fields}

2.1. \textit{Weisst Du wieviel Sternklein stehn}?

Horne (2002) gave some statistical estimates of the number of targets in the \textit{Eddington} fields based on cumulative star counts from power-law distribution functions, taking into account interstellar absorption at 1 mag/kpc. The re-

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results strongly depend on the direction of the field (i.e. the galactic latitude) and, of course, on its size. Currently, the PF-field covers a 25 square degree FOV. Horne's updated numbers (see Horne 2003) are shown in Table 1.

Note that Table 1 contains all stars in the field down to \( V = 20 \). These upper limits should then be reduced according to the technical and operational mission constraints. The first and most important constraint is the limited down-link bandwidth, which implies that only a certain number of windows of a few tens of CCD pixels can be read and processed (the exact number of pixels per window is not yet fixed). Secondly, the industrial telescope and CCD studies by Astrum and E2V suggest a defocusing of \( \approx 10 \) arcsec for the PF-field, which is sufficient for good PSF sampling even in the outer parts of the chip(s) in order to reach 10 ppm precision on the targets brighter than \( V \approx 12 \). Crowding by background targets becomes the limiting factor at the faint end and will likely exclude ultra-precise photometry for targets fainter than around \( V \approx 17 \). Thirdly, data sampling will also impact on the type of possible auxiliary science. For example, very high data sampling, with integrations of 1 s or less, would be needed for stellar-flare monitoring, while only a very low sampling rate is needed to follow stellar analogs of the solar 11 yr cycle. In any case the envisioned standard integration time of 8 s for the PF-field would lead to saturation in all stars brighter than \( V = 11 \) at a defocusing of 10 arcsec while an integration time of 1 s for the AS-fields would saturate all stars brighter than \( V = 6.5 \) at 30 arcsec defocusing (numbers courtesy C. Catala, see Catala 2003 for more details). Summing up these constraints, the cumulative number of available targets for a 25 square degree FOV at \( b = 5^\circ \) would be 300 stars brighter than \( V = 10 \), 1000 stars brighter than \( V = 12 \), 10,000 stars brighter than \( V = 15 \), and 100,000 stars brighter than \( V = 17 \). However, these numbers are likely to be an overestimate at the faint end because of unconsidered additional limitations such as (1) sky brightness (which could place a faint limit at 16.5 mag), (2) cosmic-ray accumulation (expected rate at \( L_2 \) is 5 hits cm\(^{-2}\) s\(^{-1}\)), Lumb 2003), (3) crowding by extra-galactic and galactic objects such as planetary nebulae and H\, II regions and, (4), inhomogeneity across the FOV of the stellar crowding and spectral type dependency of the contamination. Overall, we conclude that the Eddington auxiliary science would strongly benefit if the CCD-saturation limit could be shifted by one magnitude to allow the observation of brighter stars, i.e. in the range \( V = 10 \) to 16 instead of \( V = 11 \) to 17.

Could ground-based, wide field imaging photometric surveys help to confirm the number estimates? As a representative example, we consider the results of the single well-observed field of a test run of the Hungarian Automatic Telescope (HAT; Bakos et al. 2002), then at Kitt Peak, now at Mount Hopkins (Fig. 1a). Its FOV is approximately three times larger than the Eddington PF-field. A total of 250 frames were taken in the course of 12 nights with 2\times240 s integrations for each frame. A list of 60000 sources was established with DAOFIND, out of which 30000 stars with an \( I_C \) mag between 6 and 13 were usable due to the background-noise limitation imposed by a 5 \( \sigma \)
criterion used by the authors. Bakos et al. (2002) found
that sky brightness is almost always the limiting factor,
read-out noise and processing noise negligible. Aperture
photometry was then performed with DAOPHOT
(Steklos 1987) and resulted in a photometric precision
of 0.01 mag (10,000 ppm) for stars with $V = 6$ to 7,
to 0.15 mag (150,000 ppm) for stars with $V \approx 13$ (Fig. 1b).
Out of the total of 30,000 stars, 1700 (roughly 6 %)
turned out to be variable according to the $J_0 > 0.75$ variability-
index criterion of DAOPHOT (see Fig. 1b, lower panel).
Note that prior to Bakos et al.’s investigation only 12 vari-
ables (and 1 suspected variable) were known in the field.
If we simply scale the above numbers to the expected Ed-
dington precision according to Eq. 2 in Horne (2002) (i.e.
at least a factor of thousand better) and extend down to
$V = 16$, we are left with the astounding result that prob-
ably all G to M stars (the stars with spots!) brighter than
$V = 12$ mag will be found variable, the fraction falling to
70 % to 50 % at $V \approx 13$ and $V \approx 15$, respectively. In other
words, there will be no shortage of targets.

2.2. What type of variability?
The question of interest here is: what physical type of
stars are these thousands of targets? Here we can rely
on an even larger sample of light curves from yet an-
other monitoring project, the All-Sky Automated Survey
(ASAS; Pojmański 2000 and previous papers). Similar in
technical layout to HAT, the approach is different in the
sense that all bright stars down to a limit of $I_C \approx 14$ in
a 300 square-degree field in the southern sky are moni-
tored. ASAS presented two catalogs (ASAS-1 and ASAS-
2; ASAS-3 is currently underway) with 4000 new variables.
A summary of these projects is given in the introduction
by Bakos et al. (2002) and K. Horne at St.-Andrews as
well as R. Hessman at Göttingen maintain web pages that
list all of these projects (among 20 or so are GRB follow-
up searches such as ROTSE and lensing surveys such as
OGLE and MACHO, as well as planet-finding searches like
STARE and VULCAN). Taking for example the ASAS-2
catalog, one finds basically two types of variables; "eclipsing
binaries" and the "miscellaneous variables" – the latter
being mostly spotted rotating stars! Their number approxi-
ately equals the eclipsing binaries in total, while
many of the latter are also spotted stars, including the
semi-detached Algol-type and the detached RS CVn-type
binaries.

3. Stellar rotation in Eddington data
3.1. Astrophysical sample constraints
As laid out in hundreds of papers in the literature, ro-
tation plays a key role at several stages of stellar evolu-
tion for almost any stellar mass. But it is the solar-type
stars that are of special interest and that also seem to be
the most complex in their evolution. First, the pre-main-
sequence phase of low-to-moderate mass stars is domi-
nated by the angular-momentum transfer from the ac-
cretion disk to the star. Then, during the early ZAMS
phase the rotation is dominated by the onset of magnetic
braking due to mass loss via a stellar wind. In the long
subsequent long main-sequence phase, the Skumanich law
applies, i.e. the rotational rate decays proportionally to
age ($t \propto 1/\dot{P}_{rot}$; Skumanich 1972). 90 % of the Ed-
dington data will come from stars in that evolutionary stage.
Later on, when crossing the Hertzsprung gap, the star un-
dergoes a rapid redistribution of internal angular moment-
um, causing increased surface rotation for a brief period.
This is also the time where many rapidly-rotating giants
show "abnormally" large amounts of freshly dredged-up
lithium, which is then depleted on a longer time scale (see
e.g. Chaboyer et al. 1995). Almost all of these stars, from
the T-Tauri phase up to the onset of the AGB, could be
coined active stars because their rotation drives a dynamo
process, which causes non-thermal atmospheric emission
that is rotationally modulated.

![Figure 2. The expected wavelength regimes for the contribution of hot
plages and cool spots to the rotational modulation of a solar-type star.
Integral-light photometry as proposed for Eddington would make up a
combined signal that is a mixture of the two competing processes. The
worst case could be that the flux deficit at longer wavelengths due to cool
spots is "filled up" by the flux increase at shorter wavelength due to hot
plages, and no net rotational modulation is detected. This would apply
to all stars in the magnitude range considered for the planet search.](image)

3.2. The filter issue
At that point we would like to emphasise the importance of
doing standard broad-band filter photometry, or at least
obtain some sort of a "blue" and a "red" magnitude (Deeg
2003), instead of integral visual light proportional to the
QE of the CCDs. The argument is that for stars with an
outer convective envelope rising flux tubes will cause cool
starspots when they traverse the photosphere but appear
as hot plages further up when they traverse the lower and
middle chromosphere. For any late-F to early-M star this means that the missing flux due to cool spots competes with the extra flux from hot plages depending upon the spatial distribution on the stellar disk and the wavelength. Usually, plage emission peaks in the ultraviolet and spot emission in the near infrared (Fig. 2). The resulting integral visual light curve would then be nearly impossible to interpret. The worst case could be that the contributions perfectly cancel out and little or no rotational modulation remains. This could then be easily misinterpreted because the star would actually be very active. Of course, any quantitative analysis such as a combined spot and plage fit would be ambiguous unless one assumes constant contrast factors. A recent attempt to fit the bolometric VIRGO data from SoHO with a multiple spot and facular model was presented by Lanza et al. (2003b) (see also Lanza et al. 2003b). By subdividing the data into 14 day long data sets and assuming three active regions present simultaneously, Lanza et al. succeeded in fitting the subsets to within 100 ppm.

3.3. SOLAR ACRM DATA

We try to simulate the likeliness of the detection of stellar rotation from a time series of filter-free optical photometry. We base this on the Sun as the model star by employing the absolute fluxes from the full ACRM data set (Willison 2003) and treat it as if it were one of the many Eddington outputs, i.e. maintain the same sampling rate but condense the data into three years as for the PF-field. We note that the actual sampling for the PF-field will be significantly higher, approximately one light-curve point every 10 min for the fainter stars and \( \approx 30 \) s for the brighter stars, but the bolometric nature of the ACRM data simulates the “visual” filter of Eddington much better than, e.g., the Johnson V bandpass. Moreover, it will allow to create two separate data windows, one during sunspot maximum and one during sunspot minimum, that simulate a very active and a relatively inactive star, respectively. It will also help to emphasise the filter issue (see above) because during sunspot minimum usually no hot plages are seen due to the relative weakness of the field at higher atmospheric levels as compared to the photosphere\(^1\).

3.4. FOURIER ANALYSIS

Figure 3 summarises the results from the simulation. All periodograms were obtained with the program MUFRAK (Kolláth 1990) which performs a non-linear least-squares minimisation for unequally spaced data (see Oláh et al. 2001 for a brief description). The time axes on the plots in Fig. 3 correspond to the \( \approx 9000 \) days of continuous observations from ACRM-I to ACRM-III (see the Web site www.acrm.com). The PF-field data will have a baseline of approximately 3 yr baseline, i.e. a factor of \( \approx 8 \) shorter, which means that the 11 yr cycle becomes a 300 day variation in the simulation. This would be approximately the longest period that we could detect (at 2.5 cycles). Such rotation periods indeed exist for active stars, e.g. for the G5 sub-giant HR1362 (Strassmeier et al. 1999).

The first – fully blind – periodogram is shown in the right panel in Figure 3a. It is dominated by the 11 yr cycle and, clearly, the solar rotation period at approximately 0.037 cycles per day would have been missed. However, any automatic period-search routine could easily incorporate a pre-whitening process by which the largest detected peak is removed and the procedure repeated until no power above a certain detection threshold is left, a procedure that is routinely applied in asteroseismology (e.g. Breger et al. 1999). However, once we have pre-whitened the solar ACRM data and run the periodogram – this time not “blindly” – on the data thus treated, the result remains the same as above (Fig. 3b). The 0.037 cycles per day peak would have been still missed, but at least is now seen as the fifth strongest! The next logical consideration would be that we presume more active stars to be more likely to show better defined rotational modulation; and thus select comparably more active stars for the preparatory work. Unfortunately, the opposite is the case for our simulation with the ACRM data. Fig. 3c shows the two data windows for sunspot maximum around 1982, and for the sunspot minimum around 1987. Modulation is evident in both time series but the periodogram for the spot-maximum window in Fig. 3d reveals only mostly spurious periodic. The rotation would have been still missed! Only the spot-minimum phase clearly revealed the 0.037 cycles per day peak in its periodogram (along with two equally strong spurious peaks!). The reason for this is explained below.

As an active region evolves, the magnetic field spreads into an increasingly larger area and transforms from spot through plage to enhanced network state. Neighbouring active regions in different state of activity may interact. As a consequence, the rotational modulation is smeared out in the broad wavelength range of ACRM, whereas it remains observable in other narrower wavelength ranges. We demonstrate this “filter dependency” using daily solar measurements obtained in the 10.7 cm radio wavelength at Dominion Radio Astrophysical Observatory (DRAO) at Penticton, Canada (Tapping & Charrois 1994) between 1972 and 1997 (the same duration as for the ACRM dataset). Radio flux originates in the chromosphere, and is a good proxy for solar magnetic activity. The rotational signal clearly appears in the decades long radio dataset, in the pre-whitened data with the cycle period, and in the subsets at activity maximum (1979–1982) and minimum (1984–1987) as shown in Fig. 4. The subsets were
Figure 3. Results from the Fourier analysis of the ACRIM data. The original data are shown in a) in the left panel. The straightforward amplitude spectrum of the raw data is shown to the right. Clearly, only an analog of the 11 yr cycle would have been found. b) shows the results after application of a pre-whitening filter, which removes the 11 yr variability. Note that the solar rotation period is at around 0.037 cycles per day. There is a peak at that period, but its amplitude is only 0.055, we would most likely not have recognized as significant if not known a priori. c) shows the two data subsets indicated in the left panel of b), separating two states of magnetic activity, and d) shows the respective periodograms.
Figure 4. Results from the Fourier analysis of the 10.7 cm radio DRAO data. The panels are in the same order as for Fig. 3. The solar rotation period around $0.037$ cycles per day shows up in all spectra, contrary to what is found for the ACRIM data. Note, that the pre-whitening basically does not affect the pattern of the spectrum around the rotation frequency, since it is far from the activity cycle frequency. The two subsets in c) and d) correspond to the same dates as for the ACRIM data (Fig. 3). In the periodograms of the subsets, even the sign of differential rotation is found. See the text for further discussion.
3.5. Wavelet analysis

A further test was made with the ACRIM data using Morlet wavelet analysis to check if this method could help in finding stellar rotation when the Fourier technique fails. We used the program package TiFRAN (Time-Frequency Analyser, Kolláth 2002, see Csubry 2002 for details). This program uses several different methods of time-frequency analysis like short-term Fourier transforms, Morlet wavelets, and general-purpose time-frequency distributions like the Wigner distribution, the Choi-Williams distribution etc.. The appropriate version for the given task can be chosen by the user. Time-frequency methods can recover periods that are variable in time. The shortcoming is that con-
timous equidistant datasets are necessary. This require-
ment, however, will be fulfilled by the future Eddington
data.

In a recent paper, Hempelmann (2003) applied a wave-
let period-search technique to a subset of the ACRIM-I
data. His (preliminary) result is that the solar rotation pe-
riod is not recovered unambiguously during sunspot max-
imum around 1982 but is briefly detected during sunspot
minimum around 1986.

Figure 5a shows the results of our wavelet analysis of
ACRIM data taken at solar activity maximum and min-
imum just as in Fig. 3. The dataset was transformed to
equidistant points using a spline interpolation. Periods of
about 30 to 32 and 21 to 24 days were found in both data
segments with high power at some time intervals. With
lowers power the signal was present around 27 days (0.037
cycles per day) is present in both datasets. These frequen-
cies can also be found as peaks in the Fourier spectra of
the corresponding panels of Fig. 3. Unfortunately, no de-
finite result on the rotational period of the Sun is recov-
ered with the wavelet method either, only a value variable
value between 21 and 32 days. The wavelet analysis of
the radio data, on the other hand, unambiguously show
the rotational period of the Sun with the highest power
for both activity maximum and minimum as displayed in
Fig. 5b. The DRAO measurements are made always in the
same time of the day so the dataset consists of equidistant
points. This analysis shows that the rotational period is
generally shorter at activity minimum, in accordance with
the Fourier results (Fig. 3) and with the solar butterfly di-
agram from spatially-resolved observations.

We conclude that the two methods - Fourier and wave-
let - are useful for different tasks that may appear in
the Eddington data. The wavelet analysis goes through the
data in appropriate small steps, this way adding a third
dimension (time) to the analysis. Therefore, it is a
powerful tool for finding variable periods and/or giving a
guess for the rotational period when the Fourier analysis
fails. Fourier analysis, on the other hand, uses the entire
dataset, assuming the presence of constant frequencies and
thus helps finding the differential-rotation signal.

4. DIFFERENTIAL SURFACE ROTATION

4.1. Why bother?

Stellar surface differential rotation is crucial to under-
stand magnetic activity of late-type stars. The magnitude
and sign of the differential rotation pattern puts tight
constraints on the possible large-scale magnetic config-
nurations of stars with convective envelopes (e.g. Moss &
Tuominen 1997; Kitchatinov & Rüdiger 2000) and will
eventually tell us something about the underlying dynamo
process. However, measuring differential rotation is not
without ambiguity and only one or two methods allow the
extraction of the sign of the differential rotation. Conclu-
sive determination of differential-rotation parameters in
a large sample of stars would settle questions about the
type of dynamo that is preferably operating in very active
stars compared to less active stars such as the Sun (e.g.
\( \alpha \) versus \( \alpha^2 \); Brandenburg & Dobler 2002) and, equally
important, provide insight as to whether magnetic cycles
are related to the strength of the dynamo.

As shown in the previous section, the differential ro-
tation can be recovered from solar data made in suitable
and narrow wavelength ranges. In the following section we
test whether the weaker differential rotation frequently ob-
erved on stars (1 to 2 orders of magnitude lower) can be
detected in Eddington data.

4.2. DISCRETE FFT OF FULLY ARTIFICIAL DATA

In this section we perform a forward calculation of an arti-
ficial light-curve series from a differentially rotating model
star and then perform a detailed Fourier analysis on that
"data". The forward computations are done with the spot-
modelling code SML (Ribarić et al. 2003), which is based
on an analytical expression of the fractional light con-
tribution from a rotating sphere with an arbitrary number
of spots on it. For the present simulation we chose five
cool spots of equal size but situated at increasing lati-
dudes such that they span the entire hemisphere. Spot 1
is at the equator, spot 2 at +20°, spot 3 at +40°, spot 4
at +60° and spot 5 at +80°. All other stellar parameters
were chosen to match the UZ Librae system, a well-studied
spotted star (K2III; see Ołah et al. 2002a). The rotation
period, at the equator, \( P_{\text{eq}} \), was fixed to 4.68 days,
while a differential-rotation coefficient \( \alpha = (P_{\text{pole}} - P_{\text{eq}})/P_{\text{eq}} \)
on of 0.04 was employed to simulate the latitude-dependent
rotation rates (the solar value is approximately +0.2). A
positive \( \alpha \) means solar-type differential rotation, in the
sense that the equatorial regions rotate faster than the po-
lar regions. A sampling of four points per day over three
consecutive years then gives a data set of the precision
and duration expected for the Eddington PF-field.

Figure 6 shows the results. The time span in the plots
in Fig. 6a is very large compared to the "data" resolu-
tion and, as a consequence, the actual modulation due to
rotation is not obvious to the eye (top panel). What we
see instead are mostly the beat periods between the five
rotational periods at the various surface latitudes. The
top panel nevertheless is very close to what we expect
from Eddington. The middle panel in Fig. 6a shows the
same data as in the top panel but degraded with ran-
domly distributed noise of up to 10 000 ppm (a factor of
100 worse compared to the top panel), which is a conser-
native value for ground-based photometry of a \( V \approx 14 \)
mag star. The data in the bottom panel additionally has
seasonal and daily gaps, the standard burden of a ground-
based astronomer, and would represent a real data set
from an automatic telescope. The panels in Fig. 6b are
then, from top to bottom, the corresponding periodograms
computed with MUFRAN. The Fourier spectrum from the
high-precision data allows the unambiguous recovery of all five rotation periods to a high degree of confidence. Even more promising result, the reconstruction from the degraded data set is almost equally good, despite of its hundredfold (rms) lower precision. This means that we may apply the search for differential rotation to all stars in the PF-field, even as faint as $V = 17$, as long as the time coverage is 3 yr.

4.3. Discrete FFT of semi-empirical data

Figure 7 shows the results of a test very similar to that described in Sect. 4.2 but using real time-series photometric data of the spotted star UZ Librae in order to create a semi-empirical (but still artificial) data set. Again we used the spot-modelling code SML but, contrarily to the previous test, we first fitted the real data of UZ Librae as well as we possible – these results are shown in Oláh et al. (2002a) in a slightly more elaborate way – and then used the fit as our new “data” set. The top panel in Fig. 7a shows this data degraded to a randomly distributed rms precision of up to 10 000 ppm, similar than for the previous test. The middle panel shows the same data with three annual observing gaps while the bottom panel repeats the data with additional daily gaps. The respective Fourier spectra are again shown in the panels in Fig. 7b.

The results are still promising, in that the three rotational periods from the asymmetric polar spot, its appendages at high latitude, and from two equatorial spots were unambiguously recovered. However, when seasonal and daily gaps broaden the Fourier window function and consequently shift more power into the side lobes, the recovery becomes increasingly uncertain. As a consequence weaker signals, as from the polar-spot appendages, will be lost and power will be distributed among the other frequencies (and, of course, their aliases). The recovery in the
bottom panel of Fig. 7b represents the standard ground-based case and, despite the fact that the main frequency was still recovered correctly, clearly shows the ambiguity to interpret the Fourier spectrum. Obviously, only the data from space (or from concerted multi-site years-long observing campaigns from the ground) can conclusively overcome this ambiguity.

4.4. APPLICATION TO THE SPOTTED STAR UZ LIBRAE

Oláh et al. (2003) analysed a time series of nine consecutive years of high-precision (ground-based) photometry of the spotted RS CVn star UZ Lib by using the discrete Fourier-transform technique and a non-linear least-squares minimisation. The main frequency of 4.77 days due to stellar rotation was resolved into three individual frequencies separated by −0.2 % and +0.4 % around the main frequency. The stability of the spot pattern over many years, as derived from our contemporaneous Doppler images (Oláh et al. 2002b), allowed us to relate the different periods to spots at different latitudes, and thus the direct determination of the strength and the sign of the differential rotation. The main period originates from the equatorial surface regions and is practically the same as the orbital period from independent radial-velocity measurements (UZ Lib is a spectroscopic binary), suggesting that the stellar equator is tidally locked to the orbital motion. The higher latitudes rotate slightly faster than the equator, suggesting non-solar differential rotation with a parameter of $\alpha = \Delta \Omega / \Omega = -0.0026$, 80 times weaker than the solar surface value, and a lap time of $P_{eq}/\alpha \approx -1,800$ days, i.e. 14 times longer than for the Sun.
5. Ground-based support for Eddington

In this paper we concentrate on the need to support auxiliary Eddington science from the ground. This support is mostly of a “follow-up” nature while the support for the core science program is mostly of “preparatory” nature, i.e. a large part must be completed before mission launch in, planned for late 2007. In principle, both sets of support observations aim to obtain the same astrophysical parameters, but the preparatory observations must cover all potential targets while the follow-ups are target dependent. It is very important to select a promising PF-field and start the preparatory observations. This is all the more urgent because we are convinced that the PF-field must be observed prior to the 2 yr ASL fields in order to remain competitive.

5.1. Constraints on the PF field

The $L_2$ orbit of Eddington constrains its pointings to be located within either of two cones perpendicular to the ecliptic plane with an opening angle of 70° each (Pavata 2003). Fig. 8a shows a schematic diagram of the situation while Fig. 8b shows the two possible continuous viewing zones (CVZ) in a projection of the sky. The regions that convolve with the galactic-latitude criterion, i.e. centred within $\pm 10^\circ$ of the plane (see Horne 2002), are then the only possible PF-fields. Because there is no obvious advantage of the regions along the northern part of the galactic plane with respect to the southern part, the decision in which of the two CVZs should be observed is also dependent on the availability of ground-based support facilities (for both preparatory and follow up work).

5.2. Ground-based support for the core mission

This section aims to emphasise the urgent need for ground-based support observations (as also detailed in many other contributions in this volume), and to summarise the main goals of such observations. Although the principal needs are the same for both astroseismology and planet-finding, the 25 square degree PF-field requires information on much fainter stars and is thus more challenging. In detail, we should carry out:

- high-resolution white-light imaging of the entire 25 square degree field down to $V \geq 22$;
- $UBVRI$ (or $ugbr$ if available) $CCD$ photometry of all stars down to $V = 20$ and/or
- $JHK$ infrared photometry of the same stars;
- moderate-resolution spectroscopy of the brighter stars down to, say, $V = 15$.

The images are needed to determine the degree of crowding due to the defocusing. The area within a radius of 5" around each PF-target should ideally be free of other targets. Because a precision better than 10 ppm is needed to detect the transit of an Earth-sized planet, any contamination by another – possibly variable – stars less than 5 mag fainter than the target should be avoided. While the broad-band optical and near-IR photometry should give us precise magnitudes, spectral types and a first-order guess of the luminosity class, the IR photometry has the capability to separate dwarfs from giants on statistical grounds (Brown 2003). Narrow-band Strömgren photometry could additionally provide metallicity and gravity information, i.e. the luminosity class. Ultimately, moderate resolution spectroscopy ($R \approx 25000$) would yield the rotational velocity and the radial velocity, and covering specific wave-

Figure 8. a) The Eddington orbit and its continuous viewing constraints. Only targets within either of the two cones are observable. b) The transformation of the two continuous viewing zones in an Aitoff equatorial projection of the sky. The thick line is the galactic equator and the plus sign marks the centre of the two CVZs. If Eddington is to observe near the galactic equator, preferably centred at $5-10^\circ$ above or below, only a comparably small fraction of the sky is available for selection.
length regions such as the Mg b feature would also give a luminosity characterisation (Latham 2003). Including the lithium region at 671 nm would even provide an estimate of the stellar age.

As laid out in Sect. 2.1 (Table 1), there is a total of approximately 300 000 stars in the PF-field, out of which \( \approx 10 000 \) are brighter than \( V = 15 \). With an average integration time of 30 min for a single \( R = 25 000 \) echelle spectrum, allowing for 5 min overhead, we need about 500 clear nights or two years of 2 m class telescope time. Needless to say, data reduction and analysis would need to be carried out simultaneously.

Standard wide-field imaging cameras with mosaics of CCDs can nowadays cover 1 square degree of field. Given that we should aim for five optical bandpasses, the workload sums up to a minimum of 125 exposures (due to overlaps between pointings, the true number is in fact closer to 150 exposures). Adopting a 2 m class telescope, an integration time of 10 min per exposure, and a comparably limited time per night (lowest air mass during meridional passage) then requires about 6 clear nights. This is a very reasonable requirement, even if only a 0.5\(^{\circ}\) FOV can be covered.

Imaging photometry in the three IR bandpasses is significantly more challenging because the FOV available is much lower than with optical CCD mosaics.

5.3. MAGNETIC ACTIVITY AND STELLAR EVOLUTION

As mentioned above, ground-based support for stellar-activity science requires mostly follow-up observations but is driven by specific science questions. For example, what is the role of differential rotation for the internal chemical mixing of stars with convective envelopes? In other words, could the surface abundance and the angular-momentum history of a solar-type star be affected by the impact of a close planet? Evidence stems from the fact that the lithium abundance spreads also with rotation i.e. with magnetic activity (e.g. Cutispoto 2002) to the observation that the FGK stars with planets show higher metallicity than those without planets (Gonzales 1998; Santos et al. 2000). Furthermore, and more importantly for the Eddington core science, the chances of finding an Earth-sized planet will depend on how well we will be able to remove the rotationally modulated signal due to stellar activity (see for example Aigrain et al. 2003). For stellar-activity science in general and stellar rotation in particular see also Goupil (2003) and Strassmeier (2002).

While Eddington could give us very precise rotational periods and, in some cases, measure the differential rotation parameter and provide an estimate of a cycle period, we still need to determine basic astrophysical parameters like temperature, gravity, and elemental abundances (or at least metallicity). The non-radiative absolute emission-line fluxes, e.g. from the Ca ii H&K emission lines, will give the degree of magnetic energy redistribution in the stellar atmosphere and thus its “non-thermal” part. A precise value of the rotational line broadening will determine the lower limit of the stellar radius that enables to compute a luminosity (in the absence of a parallax). This, in turn, places the star in the H-R diagram and allows a comparison with theoretical evolutionary models. The stars with planet transits (or the ones that turn out to be eclipsing binaries) will also give the inclination of the rotational axis.

The proposed strategy is therefore two-fold: first, obtain a moderately high-resolution high-S/N echelle spectrum for all 10 000 FGK stars in the PF-field brighter than \( V = 15 \), then obtain Strömgren uvby photometry of the stars fainter than \( V = 15 \). Clearly, this calls for automated observing.

5.4. STELLA, Gregor and PEPSI@LBT

STELLA consists of two 1.2 m fully-robotic telescopes on the Canary island of Tenerife. STELLA-I fibre feeds a high resolution bench mounted echelle spectrograph allowing for a resolving power of 50 000 in a fixed wavelength range of 390 to 850 nm, while STELLA-II has an optical imaging photometer with a 22\(^{\circ}\) FOV (Strassmeier et al. 2001; see also www.aip.de/stella). STELLA-I will see first light in late 2003 and STELLA-II will be operational one year later. Gregor, on the other hand, is a new technology 1.5 m adaptive-optics solar telescope currently being build also on Tenerife, just a few hundred meters away from STELLA. The AIP holds 100 % of its night time and will provide a copy of the STELLA echelle spectrograph (SES) for automatic night-time observations to the Gregor consortium by the end of 2006. It is currently intended to be dedicated to Eddington follow-up (and maybe preparatory) spectroscopic observations, starting in early 2007\(^2\). High-precision Strömgren photometry of the PF-field could commence with STELLA-II by late 2004, if not decided otherwise.

A further, completely new astrophysical tool will be available in late 2006 or early 2007, shortly before the launch of Eddington: the adaptive optics high resolution pressure stabilised echelle spectropolarimeter PEPSI at the 2x8.4 m Large Binocular Telescope (LBT) in Arizona. PEPSI will provide four-vector Stokes polarimetry at a spectral resolution of up to 100 000 and integral-light spectroscopy at a spectral resolution of up to over 300 000 in the wavelength range 450 to 1050 nm (Strassmeier et al. 2003).

However, we emphasise that all proposed joint Eddington-support efforts together with our Spanish colleagues on the Canary islands and our Italian and American coll-

\(^2\) Recently, the University of Göttingen has expressed interest in the project. This could significantly speed up the implementation, allowing the spectrograph to be ready by, say, 2005, i.e. at first light of Gregor.
leagues in Arizona induce a strong preference for a PF-field in the northern hemisphere.

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