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Activity science with data from the upcoming generation of space-based high-accuracy photometric data

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Abstract. A number of high-accuracy photometric missions will be launched in the next 6 years, starting with small, missions which will observe only a handful of objects and progressing to large size (1 m class), large field of view telescopes allowing the observation of up to some 100 000 stars simultaneously. While the prime science goals of these missions will be asteroseismology and terrestrial planet finding, their long-term, accurate photometric data will encode the surface activity pattern of each target star, and thus allow activity science to be performed on unbiased samples of stars of unprecedented size. The measurements which can be carried out in this way include the integrated activity level, the spot distribution and the rotation period. We discuss summarily the upcoming missions, and in some detail the activity measurements which can be performed with them. *Eddington*, an ESA mission whose primary science goals are asteroseismology and extra-solar terrestrial planet finding, and scheduled for launch in 2007, is also discussed in some detail.

Key words: techniques: photometric – space science – stars: activity

1. Introduction

Space-based observing facilities have been, in the last 20 years or so, an essential tool in the development of stellar activity science. The main thrust of space-based observational studies of stellar activity has been on the use of wavelength regions which are not accessible from the ground, i.e. the high-energy band, and in particular the UV and the X-ray band, where most of the thermal emission from the chromosphere and corona from active stars is concentrated. UV spectroscopy and thus the study of the physical conditions of the chromosphere has become, thanks to the long life of the International Ultraviolet Explorer, a mature (and almost classical) discipline; a long series of X-ray observatories (starting with *Einstein* and followed by ROSAT, ASCA, SAX, *Chandra* and *XMM-Newton*) has allowed to establish the integrated coronal temperature and X-ray luminosity in significant samples of late-type stars, and the availability of high-resolution spectra provided by the Extreme UltraViolet Explorer has allowed detailed studies of the physical conditions (emission measure distribution, heavy element abundance, electron pressure) in the coronae of a limited number of active stars. These type of studies are being further carried forward with the high resolution spectrographs on-board *Chandra* and *XMM-Newton*.

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At the same time, no new space missions [1] accessing the wavelength regions which have been the main thrust of stellar activity studies up to now are currently planned for launch in the near future (i.e. within the next 7 years). The only UV spectroscopy facility currently in operation is the STIS onboard the Hubble Space Telescope (HST), with no currently planned successor once HST is replaced by the New Generation Space Telescope, which will be optimized toward the IR band. X-ray astronomy is currently blessed with two major operational facilities, i.e. *Chandra* and *XMM-Newton*, which are planned to last for a decade or so, thus until roughly 2010. However, plans for their successors (XEUS and Constellation-X) are still not fully defined, and neither of them is a "fully approved" mission. This lack of planned new facilities could be taken to imply a lack of observational data for stellar activity studies in the future.

At the same time, however, a new generation of space-based high-accuracy white-light photometric missions are currently being developed, with at least four missions scheduled for launch in the next 6 years. While white-light photometry is a classic ground-based observational tool (and perhaps, after astrometry, the oldest quantitative astrophysical

[1] with the exception of ASTRO-E2, a Japanese-US X-ray missions with non-dispersive high-resolution X-ray spectrographs and a high-energy (up to 600 keV) low spectral resolution instrument.

Table 1. The main characteristics of the upcoming generation of space-based high-accuracy photometry missions (the first entry refers to the EVRIS instrument, developed by the French space agency CNES, was launched on the Russian mission Mars96 but was lost when Mars96 failed). The table lists, for each mission, the telescope size, the type of focal plane detectors, the field of view ("single" indicates that only one star at the time is observable), the range of magnitude for asteroseismic and for planet finding science, the observation duration and the mission lifetime, together with the foreseen number of target stars for each science goal, the orbit in which the satellite will go and the launch date. Activity studies will be possible across the whole magnitude range covered by each mission.

	EVRIS	MOST	Rømer	COROT	*Eddington*	*Kepler*
Tel. diam.	9	15	32	30	4×60	95
Detect.	PM	CCD	CCD	4 CCD	4×10 CCD	42 CCD
FOV (deg^2)	single	single	single	3.5	35	105
V (seismo)	3.5	0–6	0–6	5–9	8–12	–
V (planet)	–	–	–	12–15	10–18	10–14
obs. dur. (seismo)	20	30	40	10–150	30–60	–
obs. dur. (planet)	–	–	–	10–150	3+ yr	4 yr
lifetime (yr)	0.7	2.5	2.5	3	2+3	4
# targets (seismo)	10	10	30	150	50 000	–
# targets (planet)	–	–	1000	120 000	500 000	–
orbit	to Mars	LEO	Molniya	polar	L2	trailing
launch	1996	2002	2005	2005	2007	2007

measurement), the upcoming generation of space-based missions will perform measurements reaching accuracy levels (due to the atmospheric scintillation) and duty cycles not accessible from ground and thus allow to explore new physical parameters (and domains).

The key scientific goals of all of the space-based high-accuracy photometric missions are to perform asteroseismology and/or to search for extra-solar planets. Asteroseismology will be done through accurate determination of the stellar oscillation frequencies as reflected in the light curve (as it has been done already for a long time on the Sun, both with ground-based networks, i.e. the GONG and BiSON networks and with some of the instruments onboard the SoHO satellite, e.g. VIRGO). The search for extra-solar planets will be performed by searching for the small decrease in stellar light caused by the transit of the planet in front of the parent star. Both scientific goals rely on the same type of observational data, and have similar observational requirements, so that they can be advantageously implemented on the same space-based mission (as indeed done on COROT and *Eddington*). At the same time, high-accuracy photometric data will unavoidably carry the signature of stellar activity processes, and thus will allow a new generation of activity studies to be carried out. The interest in understanding the effects of stellar activity on the white light photometry is therefore shared by all astronomers planning to use the data, as proper understanding (and thus removal) of the activity signature will be essential to effectively analyze of e.g. the planetary transits present in the light curves. As it often happens, one person's noise is somebody else's signal.

2. Mission overview

A number of space-based photometric missions is currently planned for launch between 2002 and 2007–2008. The present section gives a very quick overview of their characteristics, while the interested reader is referred to the specific documentation (and to the Web sites) for more detailed information for each mission. The payload of all high-accuracy photometric missions is composed by an optical telescope and a CCD-based camera. The simpler missions have small telescopes (few decimeters) with single CCDs at their focal planes and take photometric measurements of a single star at the time. Both MOST (to be launched at the end of 2002) and Rømer (whose status is somewhat uncertain, but which could be launched sometime in 2004–2005) fall in this category. They will be later followed by larger telescopes (1 m class) with a field of view of several degrees and CCD mosaic panoramic cameras, which will be able to observe tens of thousands of stars simultaneously. *Eddington* and *Kepler*, both scheduled for launch in 2007, belong to this group. COROT (scheduled for a 2005 launch) will represent an intermediate step, with a moderate-size telescope allowing the observation of a total of some thousands of stars along the mission's lifetime.

3. Observational characteristics

The key observational characteristics of space-based high-accuracy photometric measurements are the following:

- High relative accuracy (up to $\Delta F/F = 10^{-5}$ over 15 min).
- Long duration (up to 3–4 years on the same field).
- High duty cycle ($\gtrsim 90\%$)
- Relatively high-frequency temporal sampling (tens of seconds to tens of minutes).
- Large, unbiased samples (for the larger missions).

The high accuracy is a key requirement for both the primary science goals (asteroseismology and planet finding), given that the depth of a transit event due to an Earth-Sun-like planetary system is only $\Delta F/F = 10^{-5}$. Also, both asteroseismology and extra-solar planet finding need long observing runs. Asteroseismic observations need to achieve good resolution of the oscillation frequencies, with typical observing times ranging from one up to several months. For planet finding, the key requirement is to observe repeated periodic transits; to properly sample the orbit of an Earth twin three transits must be observed at a 1 yr interval, so that the relevant missions plan to point toward a target field in their continuous viewing zone for 3 to 4 years non-stop.

Similarly, both observing goals need high duty cycles, asteroseismology to avoid aliases and "side lobes" in the oscillation frequencies (induced by gaps in the observations) and planet finding to avoid missing the transits. Given that typical oscillation periods for solar-type stars are of a few minutes, their light curves need to be sampled at one minute (or better) temporal resolution. For planet finding, transits will typically last a few hours, so that the light curves need to be sampled at a resolution of 10 minutes or so. Finally, the large field of view of the more performant mission will allow simultaneous observation of large (and unbiased) samples of stars,

The observing program of these missions will include several different stellar types, including some "classic" targets of stellar activity investigations. In particular, stars in young and old open clusters will certainly be observed, as well as large samples of (serendipitous) field stars and old (including Pop. II) solar type stars, pre-main sequence stars in star-forming aggregates and giant stars.

The main observable produced by the space photometry missions will thus be long-duration, high-duty cycle light curves for all the target stars, with a target list which will span a wide range in stellar characteristics (age, mass, chemical composition, environment, etc.).

Whether some level of color information in the data is needed and/or useful for the main scientific goals of the missions is still somewhat disputed. MOST will be a pure white-light photometer, as will *Kepler*. COROT will have color resolution for its planet-finding camera, while the asteroseismic camera will be white light. Rømer will have two color bands, while for *Eddington* the matter is still open. Most activity-related observational goals would likely benefit from color capabilities.

4. Activity science with high-accuracy photometry

Photometric observations have been used to perform activity studies from ground already for a long time. The space-based data which will be available in the future will thus allow to perform the same type of studies, with better accuracy and time coverage. In this case the question "why do it from space when you can do it more cheaply from ground?" does not apply, as the data in question will be obtained for a different purpose which cannot be achieved with ground based data, and activity science will only be a secondary science goal. At the same time, some novel measurements will be possible which are not achievable with ground based data.

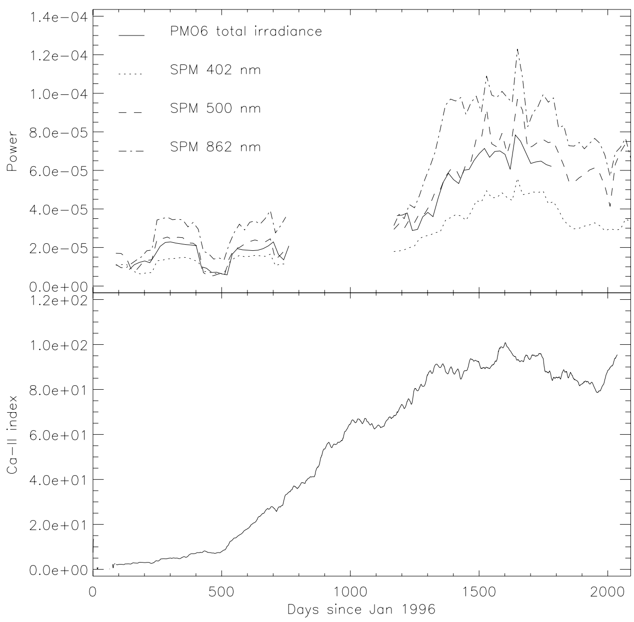

Fig. 1. Top panel: The low-frequency power in the Sun's variability from total irradiance as measured by VIRGO/PMO6 and from the three narrow channels of the VIRGO/SPM instrument, determined from 180 day-long sections of data at 20 days intervals. Bottom panel: The disk-integrated Ca II K-line index over the same period (data courtesy of BBSO). The correlation between all 4 VIRGO datasets and the Ca II index is excellent.

4.1. Activity level

While no "direct" activity indicator is present in the integrated white light output of a star (i.e. equivalent to the X-ray luminosity, or to the Ca II index), some recent work has shown that the light-curve still indirectly encodes the activity level to a very good level of detail, as shown in Fig. 1. It has been known since some time (through the analysis of data from SoHO and predecessor experiments, e.g. Harvey 1985, Andersen 1991 and Andersen 1992), that the Fourier power spectrum of the solar white light curve can be parametrized through a number of power laws, the ones at faster time scales encoding (and thus measuring) the granulation-induced noise, and the ones at slower time scales (days) encoding the noise induced by the emergence, evolution and disappearance of sunspots and thus of active regions. The variability associated with individual sunspot groups is indeed well visible in the solar white light curve.

Observations carried out in the context of the Mt Wilson HK project have shown that the level of chromospheric emission as measured through the Ca II varies across the solar disk and is higher where active regions are present. The disk-integrated Ca II emission globally increases from solar minimum to maximum activity levels [2]. Indexes such as the Mt Wilson $R_{\rm HK}$ index have been constructed to measure emission levels in Ca II in a range of stellar types and commonly are used to monitor their activity levels (Baliunas et al. 1995).

As visible in Fig. 1, the low-frequency power in the solar white-light output correlates very well with the disk-

[2] http://www.mtwilson.edu/Science/HK_Project/

integrated Ca II index. The correlation not only applies to the average activity level, but it extends to relatively short-lived high (or low) activity episodes. Assuming that this correlation will also apply through the higher activity levels observed e.g. in young stars, high-accuracy white light photometry will provide a measurement of the activity level in each and every star observed by the photometric missions. This measurement is however not "instantaneous", as it will require the integration and analysis of at least several tens of days of data, and will thus be a measure of the average activity level throughout the integration period.

4.2. Cycles

As described above, average activity level measurements (with a resolution of one month or so) will be available for all stars observed through photometry. The dedicated planet finding stellar fields of both *Eddington* and *Kepler* will be observed for three to four years non-stop, so that variations in the activity level on this time scale will be determined. As shown in Fig. 1, the modulation due to the Sun's 11 yr cycle is clearly visible in the low frequency power in the light curve (even though the limited time base of the data used in Fig. 1 does not allow the full cycle to be seen). The Mt. Wilson Ca II data on solar type stars (Baliunas et al. 1995) show that solar-like cycles are relatively common in late-type stars, with periods ranging from some three years at the short end to periods longer than the 11 yr solar one. Thus, the presence of short-period cycles will be well determined on the target stars in the planet-finding fields, while stars with longer cycles will exhibit clear long-term variability in their activity level, which will not however unambiguously identified as cyclic in nature.

4.3. White light flares

White light flares are a common occurrence at the low-mass end (so that active M dwarfs have been named "flare stars"), and they are also observed among active binaries. Some claims have also been made of white light "super-flares" on more ordinary solar-type stars (Schaefer, King, & Deliyannis 2000); however none of the events proposed as super-flares is based on direct observations. The long-term light curves produced by the photometric missions will allow the occurrence of white light flaring events (and the occurrence, if indeed real, of super-flares on ordinary stars) to be measured in large, unbiased samples of stars.

4.4. Starspots

Stellar surface mapping through the use of photometric light-curves has by now a long history (starting perhaps with the recognition and study of the "photometric wave" in RS CVn binaries), which is well discussed elsewhere in these proceedings. Space photometry will make available the data necessary to perform spot mapping for a very large number of stars: essentially all solar type stars in "key" open clusters will be observed with sufficient accuracy and temporal baseline to allow their surface spot coverage to be determined. Spot mapping would benefit from the availability of color data.

4.5. Stellar rotation rates

Rotation rate is thought to be the key parameter determining (through its being the driving "force" of the stellar dynamo) the activity level of a star. The photometric modulation induced by stellar rotation is sufficient, given the availability of accurate photometry, to allow the determination of the rotational period even in the lowest activity solar-type stars, as demonstrated by the clearly visible rotational modulation for the Sun at solar minimum in SoHO disk-integrated light curves. The key limitation of the data produced by photometry missions will be in the observation duration, as at least one full rotational period (and preferably more) should be sampled. The asteroseismic observations performed by *Eddington* in young clusters will allow the stellar rotation to be properly measured, as most of these young stars are expected to be relatively fast rotators, which should be properly sampled in the typical observing asteroseismic observing span (typically 1 to 2 months). At the same time, the long planet-finding observations (3 to 4 yr) which both *Eddington* and *Kepler* will perform will allow even the slowest field rotators to be properly sampled, allowing the determination of the rotational period distribution in a large unbiased sample of stars.

4.6. Summary

For each and every target star which will be observed by high-accuracy photometry missions the following activity-related parameters will be determined:

- Integrated activity level (equivalent to Ca II index) at approx. 1 month time resolution. For stars falling in the long, planet-finding observations the presence of short activity cycles will thus be determined. Longer cycles will show as long-term variations in activity level.
- Rotational period.
- Surface spot maps.
- White light flaring rate (if present).

Given the fact that such measurements will be available for all stars in most nearby open clusters (for the asteroseismic observations), and for large samples (up to 100 000) of randomly selected field stars (for the planet-finding observations), it is evident that the upcoming generation of space-based photometric missions will provide stellar activity studies with an unprecedented data base. While the measurements provided will not be as detailed, for individual stars, as e.g. the coronal studies performed with high-resolution X-ray spectroscopy, the statistics and the long time coverage will be unique, and thus will provide an unbiased view of surface activity along the lifetime of "normal" stars.

5. The *Eddington* mission

Eddington is ESA's high-precision photometry mission, fully approved and currently scheduled for a launch in the 2007–2008 time frame. Among the planned photometry missions *Eddington* is the one with the broader set of scientific goals. Qua asteroseismic science, it will provide detailed asteroseismic data on a large number (some 50 000) of stars spanning the whole H-R diagram, and a wide range of ages, evolutionary stages and chemical composition. Qua planet-finding science, it will search for planets system spanning a wide range of characteristics both in terms of the parent star and of the planet, e.g. in terms of stellar mass, composition and environment, and it will be sensitive to planets ranging from terrestrial planets in the habitable zone all the way to gas giants.

The baseline *Eddington* mission in its present configuration (resulting from a still ongoing industrial study) is composed of 4 identical folded Schmitt camera, each with a 60 cm aperture. The field of view is circular, 6 deg in diameter and the focal plane instruments are 4 identical mosaic CCD camera, each with 16 chips. The cameras operate in frame transfer mode, allowing optimal, low-noise operation across a wide range of parameters. The light curves from each telescope will be combined post facto, allowing the photometric performance of a 1.2 m diameter telescope to be "synthesized". The advantages of the multiple telescope approach include ease of fabrication of the smaller optics, a more compact payload with a low center of gravity, as well as intrinsic redundancy.

The service module will be a copy of the one being built for the *Herschel* mission, allowing significant savings to be realized thanks to the use of an existing development. The mission will be launched to an L2 orbit (likely with a Soyuz-Fregat launcher), which will afford a very stable thermal environment and minimal observing constraints, including the possibility of uninterrupted long term observation of the polar ecliptic caps (where the planet-finding field will be located).

The lifetime of *Eddington* is planned to be at least 5 years, with two years allocated to asteroseismic observations and three years to the planet-finding observations. Asteroseismic observations will typically last between one and two months (with longer observations possible, if scientifically granted), so that between 10 and 20 individual asteroseismic fields will be observed, while for the planet-finding one single field will be observed non stop for three years. While the asteroseismic target fields will be the subject of an open Announcement of Opportunity (allowing for the Guaranteed Time share), it is very likely that a number of open clusters will form part of the observing program. They will likely include well known objects such as Pleiades, Praesepe and Hyades, as well as some younger stellar associations and some older clusters (e.g. NGC 188, NGC 752 and M67). Also, sky regions containing a number of Pop. II stars will certainly be observed.

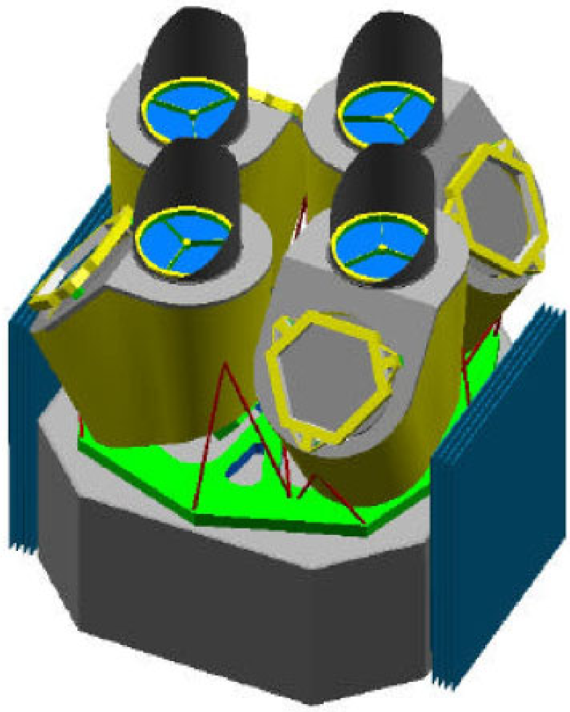

Fig. 2. The *Eddington* mission, showing the 4 folded Schmidt cameras accommodated on top of an *Herschel* bus. The solar panels are in their stowed (launch) configuration.

6. Conclusions

The upcoming generation of asteroseismology and planet-finding photometric missions will produce prime data for the study of stellar activity. Activity will fall, for these missions, in the realm of "parallel" science; while the mission design will be determined by the primary science goals, there will unavoidably be a number of trade-offs which will need to be made during the final design phase. At the time of these trade-offs the activity-related observational requirements can be taken into account as long as they are (nearly) neutral regarding the scientific performance for the primary goals and the mission cost. The time to make sure the activity requirements are folded into the process is indeed (specially for the larger missions *Eddington* and *Kepler*) now, while the final design phase is ongoing. Thus, the stellar activity community is invited to participate to the development of these missions, and will share their large wealth of results.

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