PROCEEDINGS OF SCIENCE

Stellar Oscillations and Occultations

Andrea Richichi[1]
European Southern Observatory
Karl-Schwarzschildstr. 2, 85748 Garching, Germany
E-mail: arichich@eso.org

High time resolution (HTRA) observations of phenomena such as occultations, transits and photometric lightcurves can provide direct and indirect information unaccessible to many other techniques. I will outline the scientific drivers for HTRA in these areas, and highlight some representative results in areas of stellar and planetary physics. I will review the observational capabilities available at present, in particular at the European Southern Observatory, and those that could become available in the near future.

High Time Resolution Astrophysics IV - The Era of Extremely Large Telescopes-HTRA-IV
Agios Nikolaos, Crete, Greece
May 5-7 2010

[1] Speaker

1. Introduction

Speed is one of those qualities which is intrinsically appealing to the human spirit. Regardless of differences of race, gender or age, almost invariably we are attracted by the concept of speed in sports, in technology, or even on the workplace. It is then perhaps puzzling that in the area of astronomy speed seems to have been often neglected. Astronomers have been traditionally more occupied with superlatives such as the faintest or the farthest, which are usually related to long time integrations. It is indeed true that many of the astronomical phenomena that first come to our mind have timescales of days such as stellar rotation or of years such as binary systems, not to mention of million and billions of years when we study galactic dynamics or the evolution of stars and galaxies.

And yet, an equally large number of phenomena take place at timescales which are too fast to be recorded in standard observations. But the very concept of what is standard is changing rapidly. Not only technology is allowing us to address time domains which were until recently considered beyond reach: it is also becoming possible and affordable to perform high time resolution at an increasingly large number of facilities.

Before we turn to an overview of high time resolution astronomy (HTRA) however, let us ask ourselves the question: what exactly *is* high time resolution? That this is not an idle question is evident when we consider that just at this conference there has been talk of exposures times of many seconds, as well as of picoseconds. Let us take 1 second as an arbitrary dividing line between the realms of fast and slow resolution, and we see that HTRA covers nine orders of magnitudes. If we were to roll this over, then we would have to call low time resolution anything using exposures times from 1s to 30 years. Which goes to show that such a time-oriented definition of HTRA covers in fact a very wide and diverse range of phenomena, that cannot be easily grouped together and that require quite different technological approaches.

In the present contribution, I will restrict myself to a number of stellar phenomena that are best studied at time resolutions of 1s to 1ms, and that can be studied with similar instruments. These are schematically shown in Figure 1. In Section 2 I present a brief overview of these phenomena and their importance in modern astrophysics. In Section 3 I provide a brief review of the challenges and achievements in the area of detecrors, and I conclude with a brief outline of future prospects in Section 4.

Very important HTRA topics in the time domain below 1ms or slightly above 1s are thus not included in my arbitrary delimitation, but they have been covered at the conference by various other authors [1][7][8][10][11][17].

2. Stellar phenomena at the 1s to 1ms scale

The first and foremost quality of a star is its brightness. It is also the most inconstant. It is well known that many stars are variable with amplitudes that span a very wide range from as low as one percent to a as high as a thousand times in brightness, and which can be due to a very large number of different physical reasons. Periodic or quasi-periodic instabilities in stellar atmospheres, formation and ejection of gas and dust, winds, orbital eclipses, are only the beginning of a vey long list.

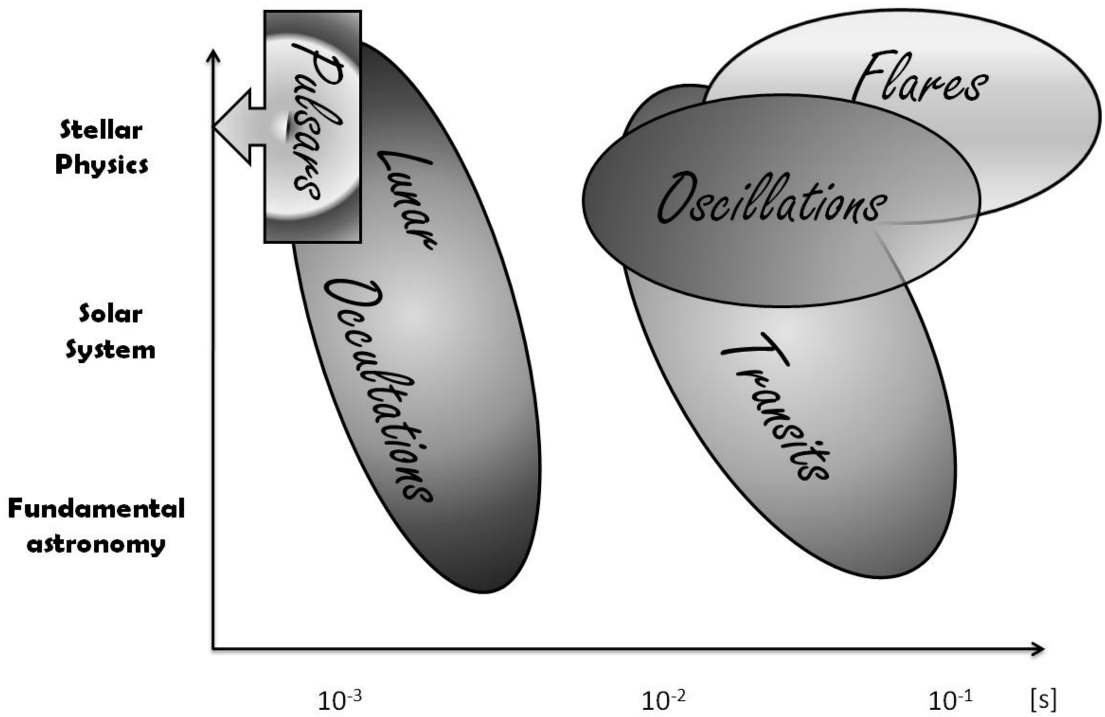

Figure 1. Qualitative classification of the phenomena described in this contribution, over an approximate domain of time tesolution and astrophysical relevance.

Those confused by all this variability might turn to our own Sun in the hope to find a shining example of stability, but also the star closest to us has its variability, with several characteristic periods. Faculæ and sunspots account for brightenings and darkenings of about 0.5% and -0.3% respectively, and their combined influence during the solar rotation produces brightness fluctuations which average about 0.1%. There are of course also longer trends, and using detectors sensitive to wavelenghts other than the visible leads to sorprising results. In the far ultraviolet and X-rays for example the Sun will appear strikingly dark and bright at different phases of the 11 years solar cycle. Longer cycles also exist and of some interest, especially at this time when global warming can easily capture the headlines, are claims of monotonical intensity changes over periods of tens of years.

In other stars, variability is known at all time scales, and we provide some examples in the following subsections.

2.1 Stellar oscillations

Our Sun leads the parade of unstable stars also in this area. Solar oscillations were first detected in the early 1960's [9] and were subsequently explained in terms of waves propagating through the solar interior. Several kinds of waves exist, the most common ones due to pressure (*p* waves, the cause of the famous 5 minutes oscillations in our Sun) and to gravity (*g* waves).

Figure 2 shows that oscillations are found in almost all kinds of stars, and also that different stars have markedly different oscillation signatures. Oscillations propagate through the stellar interior, and different kind of waves can be used as proxies to determine density and thickness of various regions of the stellar interior. In fact, in conjunction with theoretical models, oscillations can even be used to determine the age of a star. The richness of information that can be extracted explains why the field of asteroseismology, albeit relatively young, has already produced over 2,000 papers and is growing.

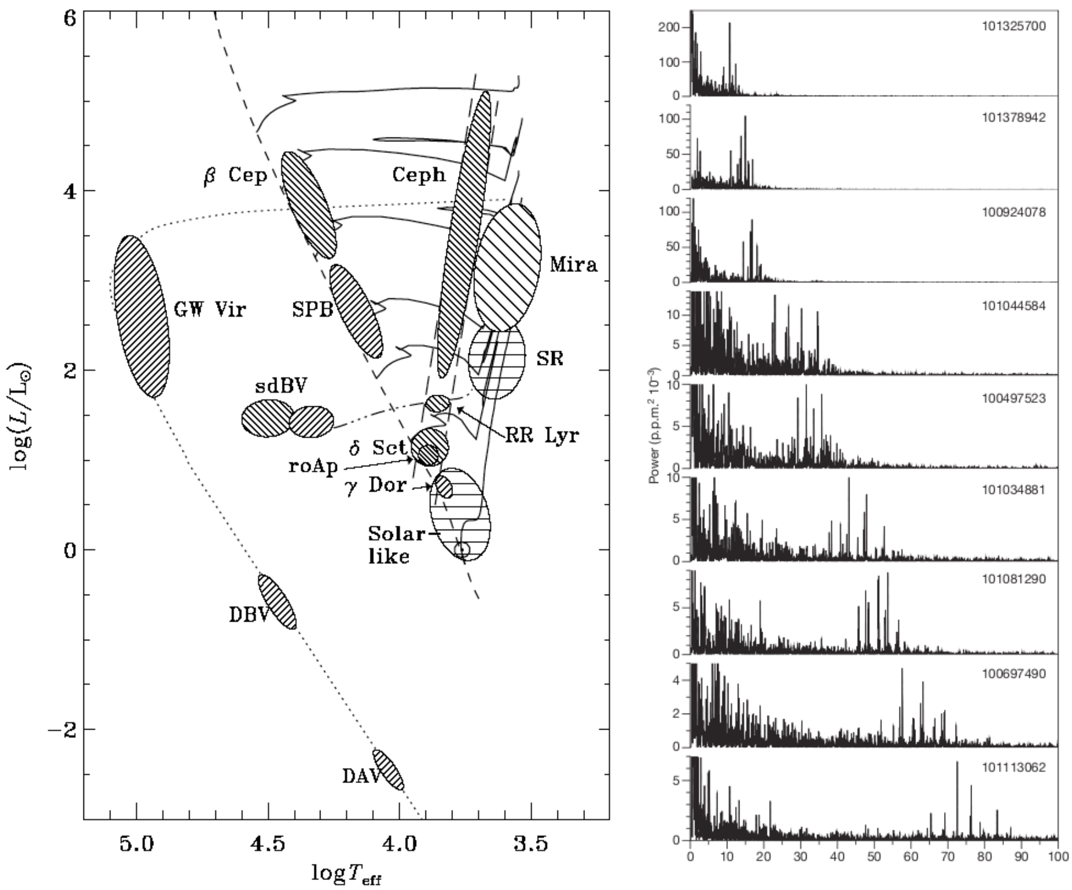

Figure 2. Left: a "zoo" of stellar oscillations. Right: CoRot measurements of the oscillation spectra of nine red giant pulsating stars. Figures downloaed and adapted from the Paris Meudon Observatory web site.

2.2 Stellar flares and flickering

Solar flares are a well known and common phenomenon, which however is not unique to our Sun. Stellar flares were observed less than one hundred years ago for the first time, but are by now known to be common in cool main sequence stars, where they can attain energy scales that vastly surpass the ones we know from the Sun. This is due to the relative strenghts of magnetic fields at the surface of such stars, which are the source of the flaring phenomenon. Flares are mostly prominent at radio and in the UV-X range, but marked increases of brightness can be seen at all wavelengths including in the visual.

Figure 3 shows an example of a very energetic flare observed on an M4 dwarf with ≈0.1s time resolution. It can be appreciated how the most energetic part of the phenomenon lasted less than one minute, and how this flare showed an even more intense repetition after just few minutes. Flares of such intensity are interesting not only because of their relevance to our understanding of stellar evolution, but also because of their significance in the growing context of evolution of planets and possibly life in other solar systems. Such energetic ("killer") flares would have dramatic effects on any nearby planets, and must be taken into account in the definition of the so-called habitable zone.

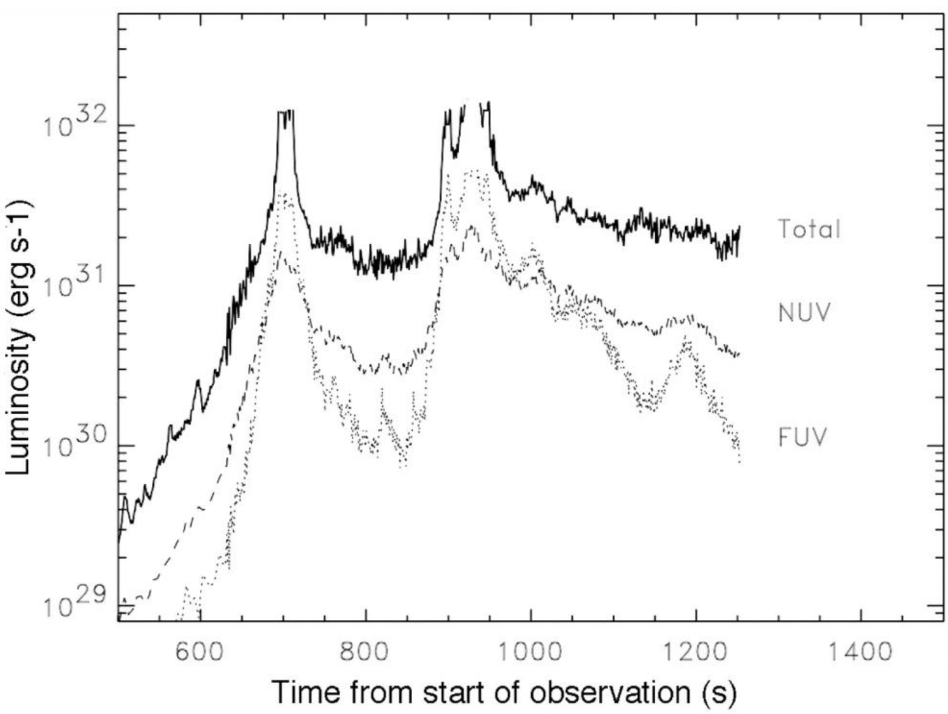

Figure 3. Example of a very energetic flare: high time resolution satellite observations in the UV of the star GJ 3685A [16]

Another form of rapid intensity fluctuations is the so-called flickering, which is observed in particular classes such as symbiotic stars and cataclysmic variables. Here, the light fluctuations have smaller amplitudes of perhaps a tenth of a magnitude over scales of less than one hour. But the phenomen seems to have a continuous time spectrum, with fluctuations of smaller amplitude seen on scale of seconds or less, and it seems to be always active. Models exist that suggest that the origin is in the interaction of the gas escaping from the central stars with the surrounding circumbinary disk, but a thorough understanding is still lacking and detailed, high-time resolution monitoring at visual and near-IR wavelengths is warranted.

2.3 Transits and occultations

Even in this field of observations, our Sun can provide a first-hand experience. Transits of Mercury and Venus have been utilized since the beginning of modern astronomy as a key source of information and observational check for models of celestial mechanics in the solar system. Today, while this primary purpose has been largely lost, these phenomena still capture immense attention from the scientific and popular communities alike, partly because of the ease of observations and partly because of their rarity. Time resolution here is not of the essence, since these transits last typically several hours (see Figure 4).

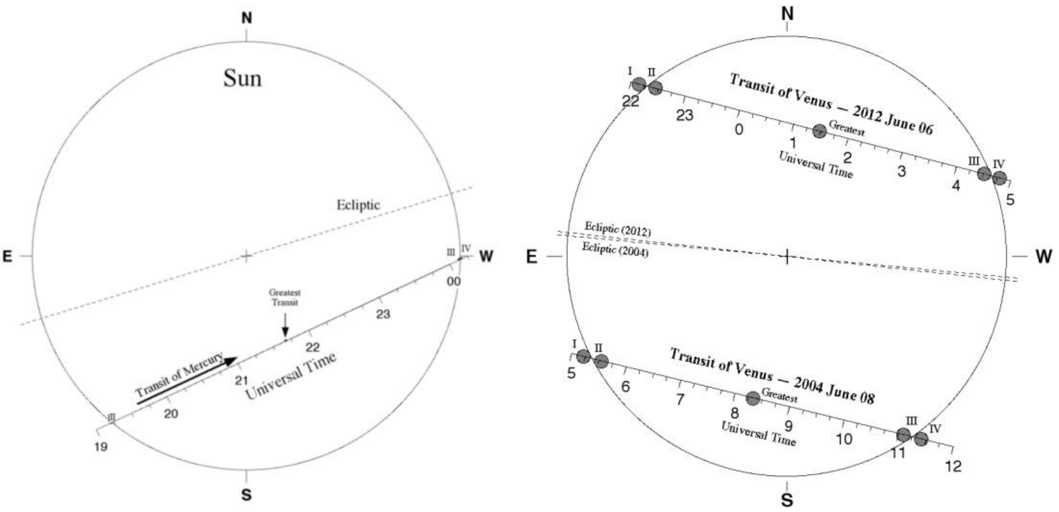

Figure 4. The solar transit of Mercury in 2008 (left), and the 2004 and 2012 solar transits of Venus. Adapted from F. Espenak, NASA/GSFC.

In other stars and planetary systems however, transits are emerging again as a key observational technique. Even as hundreds of exoplanets have been detected by radial velocity surveys and in spite of detailed and accurate measurements able to reveal even several planetary bodies orbiting the same stars, for the majority of them we lack an accurate knowledge of mass and orbital parameters due to the uncertainty in the inclination. A planetary transit in front of the host star is not only an excellent constraint on the inclination, but it also provides a very accurate and independent determination of the period. The drop in stellar flux during the transit is tiny and in fact well observable only from space, but it provides crucial information on the size and temperature of the planet. Combining all these pieces of information is the key to the discovery and characterization of rocky planets, and ultimately of other Earths.

For this, space missions like CoRot have been designed and are starting to provide a treasure trove of data. CoRot 7b captured the news in 2009 when it was announced as the smallest exoplanet yet discovered. Another example is provided in Figure 5. Recently, a small but significant statistics from exoplanets transits has been used to show that many of them appear to be on retrograde orbits with respect to the rotation of the host star, thereby challenging our experience in the solar system and our theories of planetary formation [3].

Back in our own solar system, mutual transits of planets, satellites and minor bodies among themselves, as well as their occultations of background stars, abund. They also are a key to measuring sizes, distances, and in some cases to detect binarity or detailed physical characteristics such as albedo, density, etc. Stellar occultations are especially challenging, mainly because the shadow of the occulting body is relatively small and the ground track of the occultation at the Earth is difficult to predict precisely (see Figure 6). On the other hand, these are relatively simple phenomena to observe, requiring only a photometer with sub-second time resolution, and they represent an area where the contribution of small facilities and especially of amateur observers with moving telescopes is of critical importance.

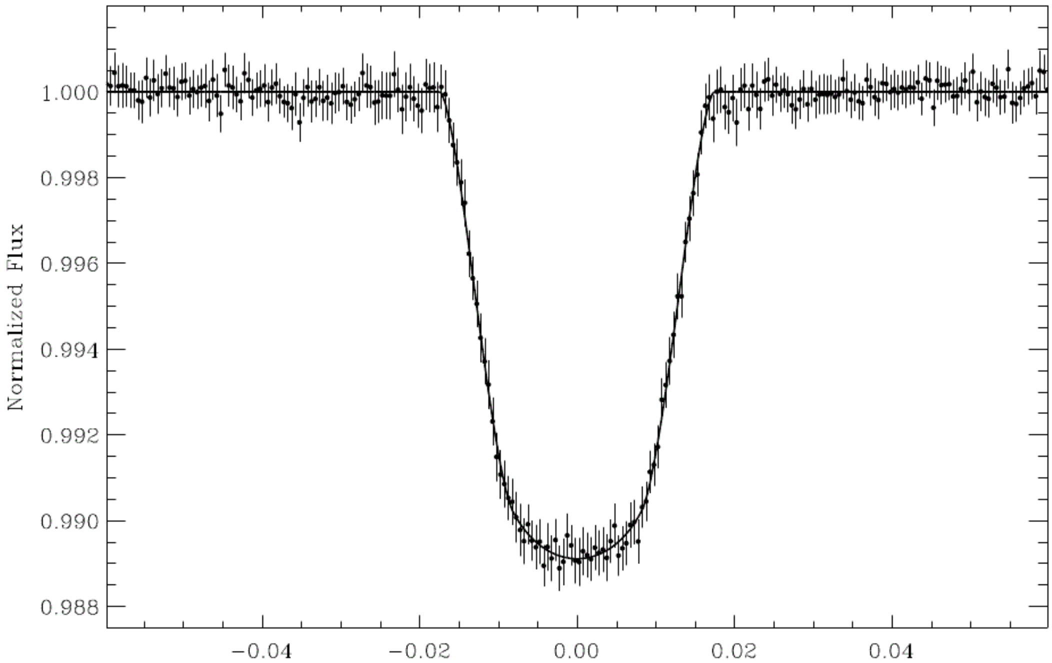

Figure 5. The transit lightcurve (dots) of Corot11-b, with all available data folded. The solid line is the best fit model. Adapted from [6].

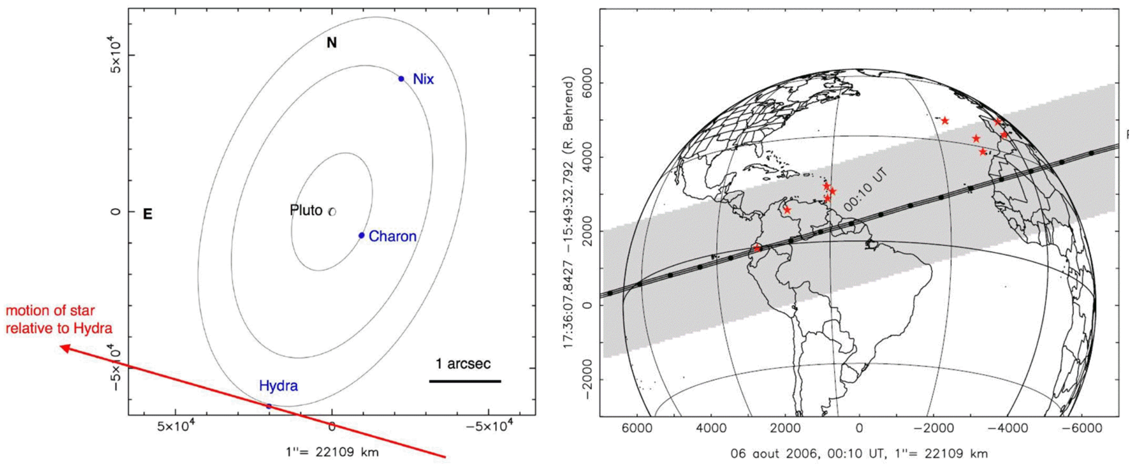

Figure 6. Predicted stellar occultaton by Hydra on 8 August, 2006 (left) and the expected ground track (right). Courtesy B. Sicardy. The observation of this event was attempted by the author from the ESO VLT using high time resolution in the near-IR.

2.4 Lunar occultations

A special mention is deserved for this particular kind of occultation phenomenon, during which a background star is covered by the lunar limb. Already more than a century ago it was realized that the phenomenon, which appears instantaneous when observed by the naked eye, could lead to angular size measurements if recorded with sufficient time resolution. Some initial misunderstandings about the optical properties of the phenomenon as well as the technological challenge of recording with millisecond time resolution put the technique in a dormient state for several decades, but starting from the 1970's lunar occultations (LO) quickly became the major source of stellar angular diameter measurements, with its unique angular resolution at the milliarcsecond (mas) level. A recent compilation [13] listed several hundreds of LO angular diameters, and a comparable number of binary and multiple star detections. Today the angular resolution capability of LO is achieved also by long-baseline interferometry, a much more complicated and challenging technique which is not subject to the random and fixed-time limitations of occultations. However, the use of modern large telescopes and fast detectors shows that LO still offers an unchalleneged combination of angular resolution, sensitivity and dynamic range [14][15].

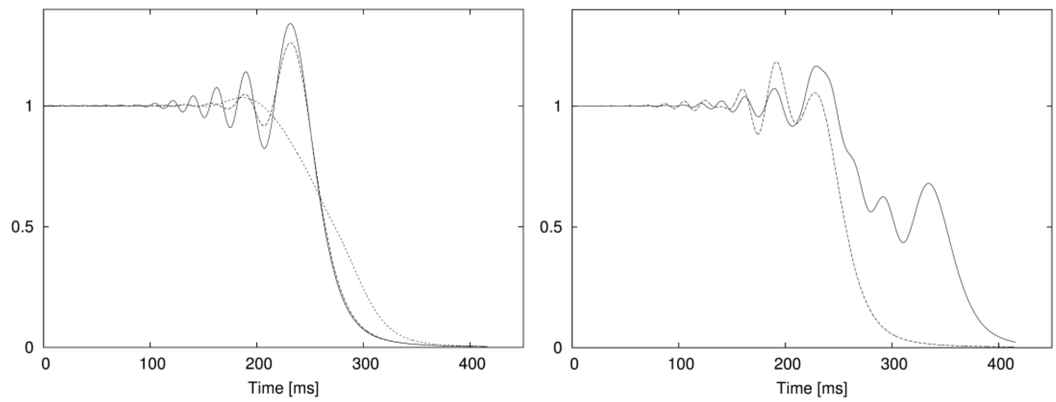

Figure 7. Left: simulated occultation light curves for unresolved (solid line), 8mas (dashed line) and 40mas (dotted line) sources. Right: same for a 1:1 binary with +30 mas separation (solid line), and a 1:2 binary with -10 mas separation (dashed line).

Only for angular sizes larger than $\sqrt{(\lambda/D)}$ the occultation phenomenon is well approximated by geometrical optics, otherwise diffraction dominates. This value corresponds to about 20-40 (mas) in the near-IR, meaning that essentially all stars produce diffraction light curves, with the lunar limb well approximated by a straight edge. The fringes have maximum contrast for an unresolved source, and are progressively smeared for increasing source sizes. This shows that measuring the contrast of the fringes is a proxy for measuring the source size, as shown in Figure 7. Two or more close stars will produce diffraction light curves that add linearly, providing the means to measure accurately separations and brightness ratios of binary and multiple stars.

LO light curves require relatively high time resolution of about 1ms for the fringes to be adequately sampled. The telescope has only the role of a "photon bucket", since the diffraction takes place at the Moon and the resolution does not depend on the telescope diameter. In fact, a smaller telescope has in principle a slightly higher angular resolution than a larger one (for the same signal-to-noise ratio), since fringes are less smeared. The effect of the telescope size, along with those of exposure time and filter bandwidth, needs to be properly modelled in the data reduction. It should be emphasized that LO only provide 1-D information along the direction of motion of the lunar limb.

3. Instrumentation

We have seen the scientific rationale for observations at time rates as fast as 1ms: how can current instrumentation cope with that? Technology is continuously improving and delivering us always larger and less noisy detectors, however when it comes to time resolution the progress is less evident. In spite of faster electronics, both in the visual and in the near-IR the increase in detector sizes has quadratically increased the number of pixels that must be read out at each exposure. Besides, the main drivers in the design and operation of such detectors is the achievement of the lowest possible noise, which is generally achieved with long, multiple exposures. At the same time, large format detectors are becoming part of standard instrumentation also at smaller astronomical facilities, while photometers and single-pixel detectors are slowly being decommissioned and becoming rare.

However, solutions exist at several observatories, and should be more widely implemented whenever possible. While slow in the read out of the full detector, both large format CCDs and near-IR arrays have in fact a rather high pixel transfer rate, usually at the 1 Mpixel/s level. Considering that most of the applications that require high time resolution are related to photometric monitoring and do not need imaging capability, it is sufficient to read out a few pixels. Tweaking of the standard observation modes is possible, in order to achieve fast read out on suitable subarrays. This has been pioneered, for example, in LO work already in the 1990's [10] and is currently implemented in a few observatories. The ISAAC instrument at the ESO VLT for example offers officially a so-called burst mode, capable of recording sustained sequences of 32x32 frames at 3ms rate [14]. Other ESO instruments with similar capability are VISIR, NACO, Hawk-I and SOFI.

Optical detectors do not normally offer a subarray read out mode, however other alternatives exist also here. CCD drift scanning has been used for LO work a decade ago [4] and remains an attractive possibility for millisecond data rates. Similar read-out schemes have been implemented elsewhere, such as the so-called HIT mode on the ESO FORS instrument. The Astralux instrument at Calar Alto (with a twin at ESO La Silla) offers a specialized EMCCD with 512x512 pixels at 30ms rate, or even higher using subarrays.

Of course, the other approach to achieving high time resolution is to reduce the array size. While this is generally against the requirements of standard imaging and spectroscopic modes, families of small format detectors have been developed and are continuing to progress due to the needs of specific applications such as adaptive optics and fast guiding. Detectors with 64^2 format and 1kHz rates, with excellent noise characteristics, are commercially available and fulfill the requirements for all of the science drivers outlined in this contribution.

The next logical step in reducing detector size is of course the single pixel detector, which has always existed but which is now in a renaissance period. Specialized APDs (avalanche photodiodes) and single-photon APDs (SPADs) exist, capable of MHz rates [2]. Examples of their application are the detectors used in the family of QuantumEye instruments [1] and in the MPE Optima instrument [8].

Finally, single-pixel InSb detectors have been traditionally used in near-IR astronomy since the 1970's, and although they are becoming increasingly rare some remain in operation such as in photometers at the SAAO in South Africa and Mt. Abu in India. Such photometers can be operated at millisecond rates, and higher if needed.

4. Conclusion and future prospects

HTRA is the key to address fundamental topics in modern astrophysics, which often cannot be studied in other ways. Although not always readily available, HTRA instruments are not particularly complicated or expensive, and in fact they can generally be developed as adaptations of existing instruments. All these considerations should let us hope that HTRA can be utilized in the future more widely than has been the case until now.

One step in this direction is to plan properly for HTRA capabilities in the next generation of extremely large telescopes. Plans for the E-ELT have been summarized elsewhere in these proceedings [5]. The superior photon-collecting capability of the E-ELT would greatly benefit the quality of HTRA observations, and extend HTRA to significantly fainter objects. At the same time, the science drivers listed in this contribution do not require imaging, so that even an early E-ELT with only a partial completion of the primary mirror or with a not yet optimal figure quality would suffice.

Clearly, there is a scope also for HTRA observations from space, where unfortunately instrumentation has been until now not readily available for very fast read-out, but where first steps in this direction are being made for example with the previously mentioned CoRot monitoring of exoplanet transits. In particular, space observations of transits and occultations would offer a dramatically superior performance from space not only because of the drastic reduction in background, but also because in some cases the sampling of the event can be largely increased from an orbiting observation point. The ultimate tool could be to use a man-made occulting screen. Examples of concept studies of solar sails and other occulting devices already exist, admittedly at very significant costs. The benefits of such occulters however would be tremendous, enabling us to choose the targets at will, to push down the limiting magnitude into the domain of extragalactic sources, and to perform real imaging from tomographic reconstruction, instead of 1-D scans as in today's LO.

References

[1] Barbieri C., these proceedings

[2] Bonanno G., these proceedings

[3] ESO Press Release 2010-16, http://www.eso.org/public/news/eso1016/

[4] Fors O., Núñez J., Richichi A. 2001, A&A, 378, 1100

[5] Hook I., these proceedings

[6] Gandolfi D. et al 2010, A&A in press

[7] Gradari S., these proceedings

[8] Kanbach G., these proceedings.

[9] Leighton, R.B., Noyes, R.W., Simon, G.W. 1962, ApJ, 135, 474

[10] Mignani R., these proceedings

[11] Patruno A., these proceedings

[12] Richichi A., Baffa C., Calamai G., Lisi F. 1996 AJ, 112, 2786

[13] Richichi A., Percheron I., Khristoforova M. 2005, A&A 431, 773

[14] Richichi A., Fors O., Mason E. 2010, A&A, 489, 1441

[15] Richichi A., Fors O., Chen W.-P., Mason E. 2010, A&A, in press

[16] Robinson, R.D., et al. 2005, ApJ 633, 447

[17] Schmitt J., these proceedings

[18] Shearer A., these proceedings