ELT precision photometry and exoplanet studies

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Abstract: An ELT is theoretically capable of extreme photometric precision on stars as faint as 15th magnitude in half an hour, potentially allowing detection of transiting extrasolar bodies as small as the earth's moon. Unfortunately, atmospheric scintillation sets a ceiling to the achievable S/N performance which is well below the photon noise limit. However, it is shown that spectroscopic techniques such as Doppler imaging, effectively remove scintillation which is well correlated over short wavelength intervals, in principle allowing easy detection of transits due to earth-sized planets.

Keywords: Techniques: photometric, (*Stars:*) planetary systems

1. PLANETARY TRANSITS AND ELT PHOTOMETRY

1.1. Introduction

The observation of planetary transits around their parent stars represents a new technique for the detection and characterisation of exoplanets. Some eight transiting planets are currently known, including the Saturnian mass planet orbiting HD149026[1]. In future, space missions will increase this number greatly. COROT, to be launched in 2006, will study some 12000 stars brighter than V = 15 while KEPLER, due for launch in 2008, will observe some 223,000 stars in a field at declination +44 degrees. Efforts are also underway from groundbased sites, where investigators have realised that small telescopes equipped with CCD cameras are ideal for this type of investigation (eg. BEST, superWASP, OGLE). Orbital radii from 0.1 to a few AU give transit periods of typically 4 to 20 hours.

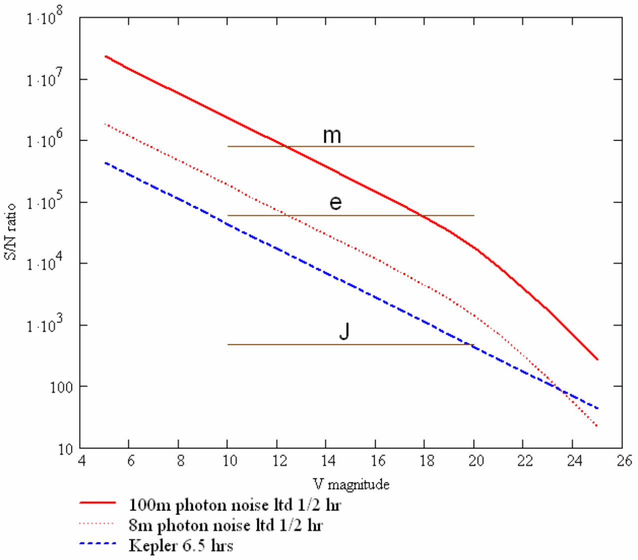

Figure 1. S/N achieved in photon noise limited cases. 5σ detections for Jupiter, earth and earth's moon are shown.

While small telescopes can detect Jupiter sized transits (1% photometry), the detection of earthsized planets is generally considered to be possible only from space. In fact, the possibility is discussed here that earth-sized planets *can* be detected from the ground during transits provided the dominant noise source in precision photometry, scintillation, can be overcome. Figure 1 shows the S/N achieved in a variety of cases, as a function of V magnitude of the parent star. The horizontal lines show the 5σ S/N ratio required to detect transits of Jupiter (J), the earth (e), and the earth's moon (m). We see that a photon noise limited 8-m could already detect an earth transit in stars as faint as magnitude 12 or so in half an hour. An OWL-type 100m ELT could detect transits by the earth's moon in the same time in stars of similar magnitude!

Of course, the performance implied in Figure 1 is generally unachievable. Even if all systematic errors in photometry are controlled, atmospheric scintillation ultimately limits the precision achieved.

1.2. Limits due to Scintillation

Atmospheric phase fluctuations which cause astronomical seeing have been the subject of large amounts of research and publications. On the other hand the study of scintillation, fluctuations in the intensity of light arriving at the telescope aperture, has received much less interest. While seeing is due to local changes in wavefront slope or first spatial derivative, scintillation is due to the second spatial derivative or curvature of the wavefront. Simply speaking, where a wavefront is curved, a focussing (or defocussing) will take place as the wavefront propagates down through the atmosphere. The result is that scintillation arising from high altitude layers and small spatial scales modulates the integrated light falling on a telescope aperture. Although the effect decreases with telescope aperture, it dominates for long integration times and ultimately limits the performance achievable. Furthermore, it affects all stars equally, so bright stars have the same fractional scintillation noise as faint ones. The most thorough recent study of scintillation is due to Dravins[2-4]. The prediction from observed and extrapolated results is that a 100m telescope, instead of approaching the photometric precision of $\Delta V \sim 10^{-6}$ in half an hour as shown in Figure 1, bottoms out at slightly better than 10^{-4}, insufficient to detect an earth transit.

2. DOPPLER IMAGING

2.1. Precision Measurements

As in adaptive optics however, there is the possibility of using correlations to remove the effects of scintillation. Unfortunately, the small scale and high altitude of atmospheric scintillation generation mean that angular correlation scales are very small and certainly less than a few arcsec. Since in any case the comparison star needs to be at least as bright as the target, this technique cannot be used except in perhaps a few very special situations. So differential photometry appears in general to not be a solution.

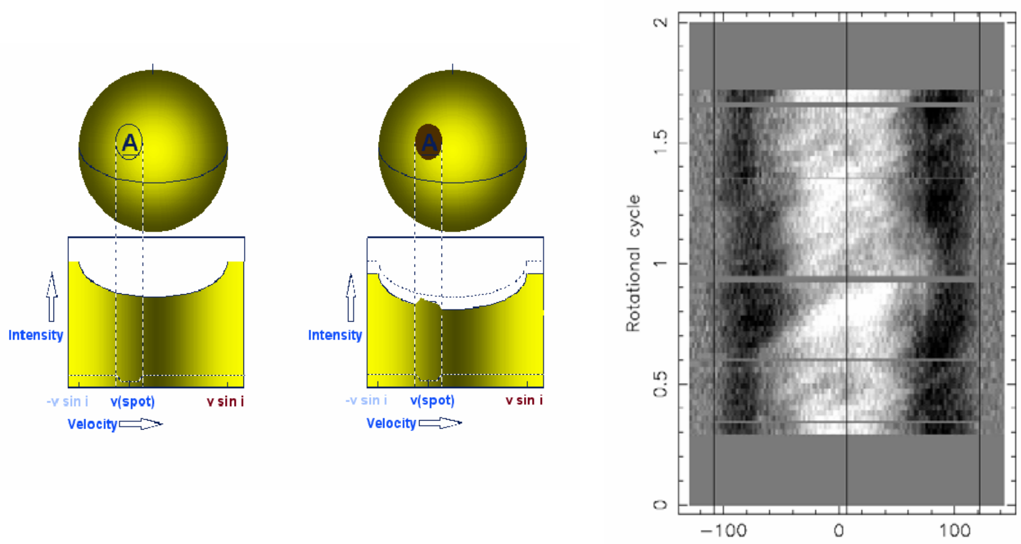

Figure 2. Principle of Doppler Imaging (left). Real data for post T Tauri star (right).

Dravins[3] points out that scintillation is generally well-correlated with wavelength, and over small (spectroscopic, say 0.1 nm) wavelength intervals should be essentially perfectly correlated. So a technique using differential changes over small wavelength intervals would offer promise, if a way can be found for a planetary transit to generate these changes.

As it turns out, planetary transits do this by default since as the planet transits the stellar disc the line-of-sight velocity of the blocked stellar surface changes with time. Over the period of a transit, changes in the shape of a spectral line observed at high resolution will occur. This is nothing more than Doppler imaging, a technique which has been used to study the sizes and latitudes of magnetic regions (starspots) on stellar surfaces. Figure 2 shows the principle of the technique (figure courtesy Andrew Collier-Cameron), in which the obscured region gives rise to an emission bump in a rotationally broadened spectral line. By taking high resolution spectra continuously in time a complete map of the surface can be constructed as shown in Figure 2 for the post T Tauri star RX J1508.6-4423[6]. A planetary transit on such a star would appear as a bright line (just as for a starspot) but with a *different* slope from magnetic surface features, since in general the transit time will be much less than the stellar rotation period. In fact the technique has already been used to study the shift in line centroid (since the stellar rotational velocity was low) in the transiting system HD209458b, by Snellen[7]. Interestingly, the technique can also measure whether an orbit is prograde or retrograde (prograde in the case of HD209458b).

Such a technique applied to a single spectral line has limited sensitivity of course, since the spectral resolution required is generally high (>50,000), and would be of little use for detecting planetary transits. However, an important advance in the doppler technique has been to bin many spectral lines and thereby improve the S/N ratio substantially. For stellar surface studies for example, 1150 lines were binned by Barnes et al[5] to give a factor of 22 improvement in S/N.

It is interesting to ask whether such a technique could give the precision required for interesting transit studies. Figure 3 shows the S/N expected in half an hour of integration for three cases – a photon noise limited 100m telescope, a doppler-imaging 100m telescope with ~1000 line binning, and a scintillation-noise limited 100m telescope. The doppler imaging is indeed capable of greatly improving the detection limit for earth transits - to a limiting magnitude of 14.

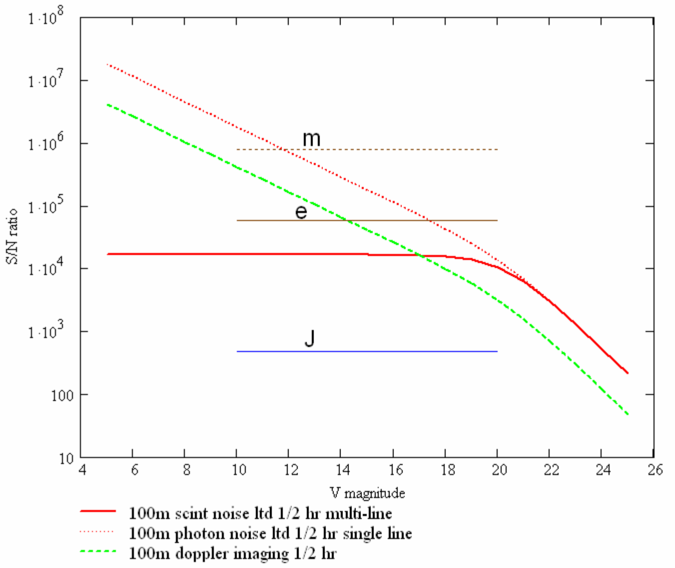

Figure 3. S/N achieved with Doppler imaging

Of course, the question of *how* an ELT equipped with doppler imaging could be used to study transits is a separate interesting problem, since one could not imagine devoting large amounts of time to blind studies, and spectroscopic multiplexing of large numbers of objects at high resolution and wavelength coverage is difficult to envision. However, a more productive approach might be to tackle objects with known Jupiter transits (discovered with other facilities) thus greatly increasing the probability of detecting other smaller bodies, since the orbital plane is then known to be close to the line of sight.

2.2. Suitable Spectral Regions

Various spectral regions could be suitable for a doppler imaging study of transits. The Barnes[5] paper used the visible region from 4778 to 7450 angstroms. Another good region would be in the IR H band, where thousands of mainly metal lines would be available at high resolution. Another interesting region is in the CO 2-1 bandhead at 2.3 microns where again thousands of vib-rot lines would be available between the telluric lines.

3. CONCLUSION

Doppler imaging is introduced as a way of removing scintillation errors which limit high precision photometry from the ground. By combining many spectral lines, sufficient sensitivity can be reached to allow the detection of earth-size planetary transits.

4. ACKNOWLEDGEMENTS

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