SHOULD *EDDINGTON* CONCENTRATE ON M STARS?

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Abstract

In a recent preprint, Pepper et al. (2002) evaluate the sensitivity of photon-noise limited transit searches for habitable planets. They conclude that these searches have the largest chance of success if they are optimised toward the surveying of M stars. Such an optimisation implies several constraints and trade-offs. The principal one is that M star surveys need to observe at fainter magnitudes than surveys of solar-like stars. The required shift to fainter magnitudes is in principle possible, as M stars require less photometric precision in order to detect transits of their habitable planets. However, relatively higher noise from sky-background and increased crowding at fainter magnitudes requires the employment of optics with adequately small point-spread functions, with consequences on the observable dynamic range.

A review of the merit of this strategy is given, first in terms of habitability of M star planets. Though being tidally locked to the central star, these planets are valuable and interesting targets. Their detection may however not be so much a primary goal as that of Earth-like planets. Second, potential implications for the *Eddington* mission are discussed, and estimates for the noise sources and stellar crowding are given. A preliminary recommendation is to optimise *Eddington* for mid-K stars, employing moderately smaller apertures. Such an optimisation should allow *Eddington* to access both neighbouring spectral classes (G and M) as well, and habitable planets with and without tidal locking may be detected.

Key words: Planets: exo-planets – habitability – target population – stellar crowding – M stars – mission design – noise sources

1. Introduction

The current design of the planet-finding part of the *Eddington* mission is focused on – and optimised for – the detection of habitable planets around solar-like stars. The guiding requirement for this design has been the ability to detect Earth-sized planets on Earth-like orbits around stars similar to the Sun. This is a very difficult objective to achieve, and current estimates (Horne 2002; Horne 2003; Deeg & Horne 2002) indicate that only a handful of such planets can be detected by *Eddington*, and furthermore require that such planets are present around a significant fraction of solar-like stars.

The starting point of this contribution was a preprint by Gould et al. (2002), entitled "The Sensitivity of Transit Searches to Habitable Planets" where the authors advocate that a space-based transit detection experiment will find significantly more planets in the habitable zone, if that search is being optimised to provide the maximum detection sensitivity for transits across M stars. This raised the two following questions:

- Are very low mass stars, especially M stars suitable hosts for habitable planets, and hence, are they rewarding targets for *Eddington*?
- Is an optimisation of *Eddington* toward M stars technically feasible? (observational aspects)

I attempt to answer these questions in the next two sections of present. In the final section, consequences of such an optimisation are discussed, toward their suitability for the *Eddington* mission.

2. M star planets as a bio-habitat

Planets around low mass stars, and especially around the lowest-mass M stars provide some significant differences to Earth-like planets with respect to their suitability as a habitat for life. These are:

1. The planets are tidally locked, with the same side always facing the central star
2. The incident stellar radiation is significantly shifted toward longer wavelengths.
3. M stars have frequent flares, which may emit a significant fraction of the stellar luminosity on timescales of the order of several minutes. They also may have large starspots that significantly lower luminosity on time-scales of weeks.

With respect to item 1., following the generally accepted approximate shape of the circumstellar habitable zone (Fig. 1), nearly all habitable planets around M stars will be tidally locked. The exception are planets on the "cold-edge" around M0 or M1 stars. Also, a fraction of habitable planets around K stars will be locked. The consequence of locking is that all stellar insolation is concentrated permanently on the same side of the planet.

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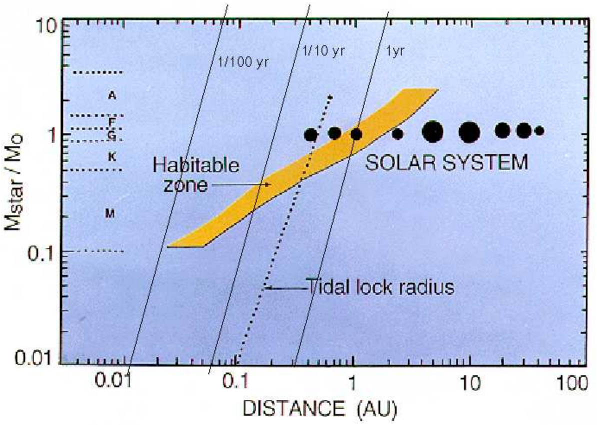

Figure 1. The extent of the habitable zone as a function of stellar mass and planetary distance, adapted from Kasting et al. (1993). Tidal locking occurs to the left of the dotted line. The solid diagonal lines are lines of constant orbital period. The periods of habitable planets around M stars range from a few days to about ten weeks.

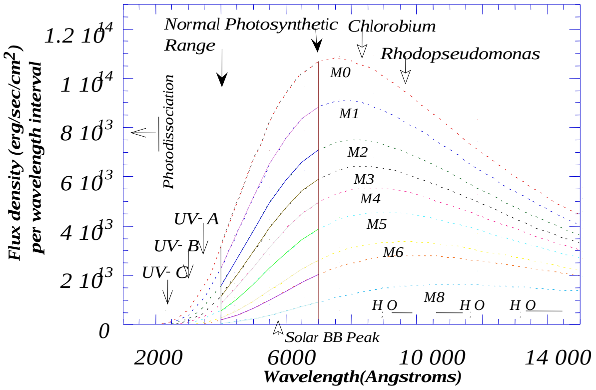

Figure 2. Approximate spectral distribution of light from M stars (from Doyle & Deeg 2002). The normal range of photosynthetic processes is indicated by the filled arrows, and the wavelength regions at which two anaerobic bacteria perform a similar process by the hollow arrows. It can also be seen that intensities for photodissociation processes are extremely low, as are all kinds of UV radiation. In real M star spectra, fluxes in the range 5000 to 8000 Åare even lower than the corresponding black-body fluxes.

Initially it was thought that these planets cannot be habitable, being unable to maintain a dense atmosphere, as it would condense out on the very cold dark side. This belief was reversed by the work of Joshi et al. (1997) and Heath et al. (1999). Joshi et al. performed numerical simulations of M star atmospheres, showing that atmospheres can survive indefinitely over a fairly wide range of conditions. Their atmospheric stability is obtained through a strong temperature mixing which is sustained by a permanent wind-pattern that transports heat from the illuminated side to the dark one. At the same time, the wind-pattern keeps temperatures on the bright side within a range that is acceptable for life. A tidally locked planet with Earth-like parameters (in terms of size, atmospheric pressure and stellar insolation) was found by Joshi et al. to have a maximum temperature of $+60\,^\circ$ at the sub-stellar point, a strong temperature gradient on the day-night equator, and a night side temperature of 0 to $-10\,^\circ$. This range is entirely comparable to the range of temperature-averages that are found on Earth (≈ -30 to $+30\,^\circ$).

With respect to item 2., the spectral distribution of low mass stars is markedly shifted toward the red. In the usual photosynthetic range (see Fig. 2), a significant flux is however still present, at levels of 3 to 30 % of the flux received by the Earth's (for a planet that receives a bolometric flux of one solar constant or 1.37 kW/m^2). Photosynthetic activity on these planets is therefore possible, at flux levels comparable to shady environments on Earth. Bacteria which perform photosynthetic processes in red light, such as the anaerobic varieties *Chlorobium* and *Rhodopseudomonas*, are known to exist on Earth. Furthermore, the extremely low fluxes from M stars in the near-UV will make an ozone layer unnecessary, and the absence of photo-dissociation of H_2O will make a moist runaway greenhouse effect impossible.

With respect to item 3., M stars are known to emit large flares and to have starspots covering a significant fraction of their surface. Flares will emit significantly increased UV and X-ray fluxes. This increase should however be kept in relation with the extremely low quiescent flux, and UV fluxes comparable to those received by the Earth will be received only over scales of a few minutes. Also, these fluxes are unlikely to have much effect at any depth within a liquid environment, and near (or beyond) the planets day/night boundary. The climatic effect of large starspots was simulated by Joshi (1999), who showed that these cause a temperature drop on the order of 20 to $25\,^\circ$ from which the planet recovers within a few weeks. Serious damage to adapted ecosystems is therefore not expected.

In summary, M star planets may have a dense atmosphere, and may maintain a wide, probably ring-shaped habitable zone, over a range of conditions that may be similar to habitable planets around solar-like stars. The possibility for the development of higher life-forms is not excluded. Consequently, M star planets are worthwhile targets in searches for extraterrestrial habitats.

3. The observability of M star planets

This enquiry was initially motivated by the claim by Gould et al. that increased numbers of detections of habitable planets would be achieved if missions like *Kepler* and *Eddington* were optimised to have M stars as principal targets. Their argument is based on scaling “laws” for the

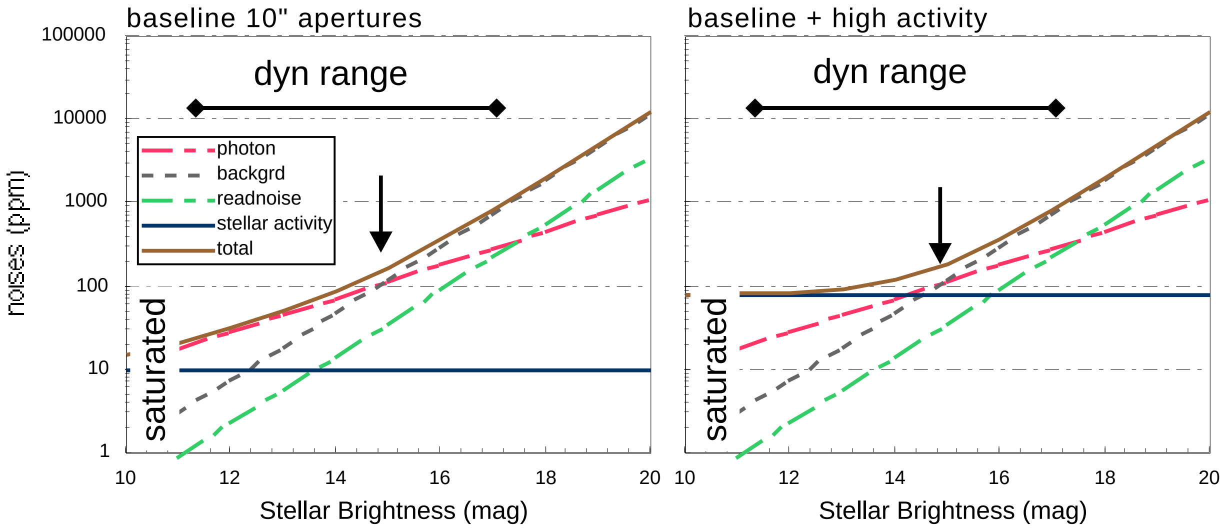

Figure 3. **Left panel***: Estimation of the various noise contributions (in ppm) as a function of V-band magnitude for* Eddington*'s baseline 4-telescope design (ESA 2002), with a 10 arcsec aperture and appropriately defocussed point spread function. The noise contributions are calculated for 1 hr integrations with a uniform sky-background of 21 mag/arcsec^2, and a stellar activity level of 10 ppm (horizontal solid line). The uppermost solid line is the sum of all noise contributions. The long dashed line shows photon noise from the target star, the short dashed line photon noise from the uniform background, and the short-long dashed line the CCD read-noise. Also indicated is the dynamical range, which is assumed to cover 6 magnitudes from the saturation limit, of $V = 11$. The vertical arrow indicates the magnitude at which photon noise from the sky-background begins to dominated over photon noise from the target star. Stars fainter than this limit are not being detected optimally.* **Right panel:** *Idem, but assuming a higher stellar activity level of 80 ppm. The magnitude range where photon noise from the target star dominates and optimal detection is possible is now restricted to magnitudes brighter than $V = 14.5$.*

number of habitable planet detections, similar to those that have previously been given for the *Eddington* mission by Favata et al. (2000) and Horne (2002). The "law" quoted by Gould et al. was adapted from Pepper et al. (2002), with the assumption that every star has one habitable planet:

$$N_{\rm pl} \propto n\ L^{3/2}\ R^{-7/2}\ L_{\rm bol}^{-5/4}$$

In this relation, the relative number $N_{\rm pl}$ of detected habitable planets is computed given the stellar density n, stellar luminosity in the observation bandpass L, stellar radius R and bolometric luminosity L_{bol}. Comparing $N_{\rm pl}$ for G stars and mid-M stars, we obtain: $N_{\rm pl}|_{\rm M}/N_{\rm pl}|_{\rm G} \approx 6 \times 630^{-3/2} \times 4^{7/2} \times 80^{5/4} \approx 10$. A transit search limited by photon noise only would therefore detect an order of magnitude more planets if it was aimed at M stars rather than at solar-like stars. It should be noted that such scaling laws contain several simplifications and assumptions, such as power-law dependencies among several fundamental parameters. More reliable results can be obtained from Monte Carlo simulations (e.g. Horne 2002; Horne 2003), which allow any kind of functional dependency to be incorporated relative ease. Nonetheless, scaling laws remain a valuable tool for first-order comparisons.

However, an important consequence of aiming at M stars is that the limiting apparent magnitude for the detection of their habitable planets will be significantly fainter (by several mag) than that for searches around solar-like stars. This results from two facts. First, habitable planets orbiting M stars have much shorter periods and hence will cause several times more transits in a light curve of a given duration. Secondly, M stars have smaller radii than solar-like stars, and a planet of a given size will cause deeper transits if it orbits and M star. Considering only photon noise, the magnitude limit for the detection of habitable planets (assuming $R_{\rm pl} = 1\,R_{\oplus}$) with *Eddington* (light curve duration 3 years) around G stars is $V \approx 14$, whereas the same limit for mid-M stars is $V \approx 18$ (Horne 2003). This shift in magnitude limits has important consequences for the design of a transit mission: as stellar densities increase approximately exponentially with magnitude, the vast majority of the planet detections will actually occur near the magnitude limit. The mission therefore needs to be designed to work optimally near the typical magnitude limit of the sample population.

4. OPTIMISING *EDDINGTON* FOR M STAR OBSERVATIONS

Considering only photon-noise, the same transit mission could observe G and M stars simultaneously and obtain optimum results for both populations. However, with a real detector, optimum results can be obtained only for a smaller range of population, with its corresponding "typ-

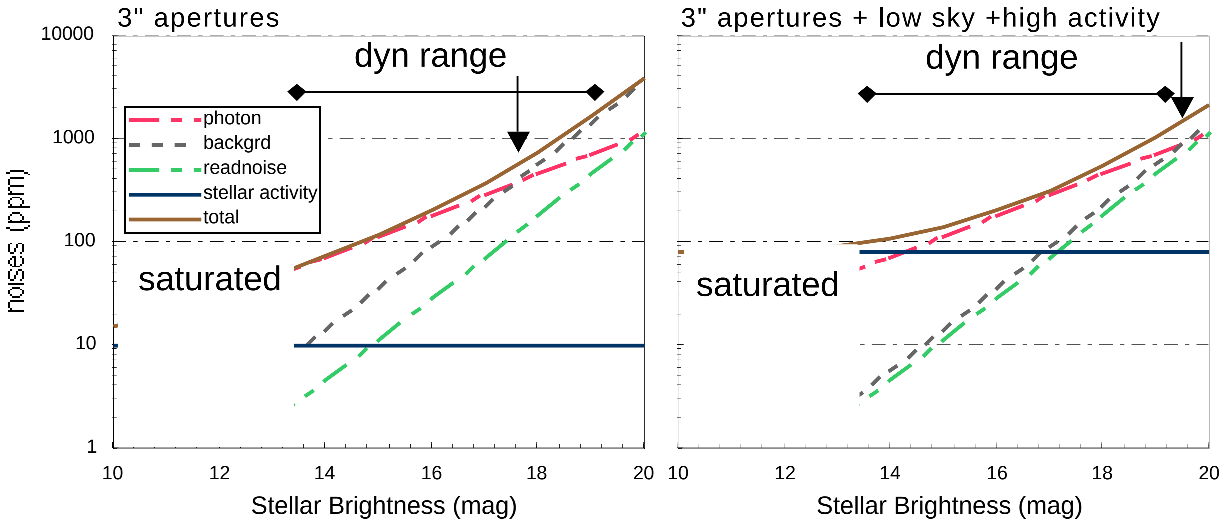

Figure 4. **Left panel:** *As Fig. 3, but assuming a narrowly focused PSF and 3 arcsec apertures. This reduces noise from the sky background, but stars brighter than* $V \approx 13$ *are saturated. Stars up to* $V \approx 17.5$ *can be observed optimally, (i.e. they are photon noise dominated).* **Right panel:** *Idem, but a field assuming a lower sky-background of 23 mag/arcsec*^{2}*, making optimum observations up to* $V \approx 19$ *possible. Photon noise dominated observations are possible over nearly the entire dynamical range of the detector. In this graph, a higher stellar activity level of 80 ppm is also assumed. However this has little effect within the dynamical range. For faint targets with* $V = 18$–19*, even an activity level of several hundred ppm will not degrade the observations significantly.*

ical magnitude". This limitation is mainly a consequence of the presence of other noise sources, of the finite dynamical range of the detector, and of stellar crowding. The current set-up for *Eddington* was optimised for the detection of Earth-like planets around solar-like stars. For this "baseline" setup, with photometric apertures of 10 arcsec diameter (and optical point-spread functions of similar size), Fig. 3 shows estimates for the various noise sources.

While this baseline design allows detections between $V = 11$ and $V = 17$, the cross over point where noise from sky-background becomes dominant over photon noise is near $V = 14.5$, meaning that the detector is not optimal for fainter samples. Given that the principal sample population (Earth-like planet orbiting a solar-like star) has its detection limit near $V = 14$, it should be mentioned that this set-up is rather sensitive to the stellar activity level (see Fig. 3, right panel). With an activity level of 100 ppm, the magnitude window were photon noise dominates nearly disappears. A relatively large point spread function (PSF) of 10 arcsec was used in the baseline design for two reasons: it allows the observation of relatively bright stars (up to $V = 11$) without over-saturation, and photometry with the highest possible S/N results from the use of a large smooth PSF with weak gradients, were the effects of intra- and inter-pixel sensitivity variations are minimised, thus limiting the noise due to the motion of the spacecraft (jitter).

An evaluation of the level of crowding in 10 arcsec apertures (Fig. 5) shows that stellar crowding increases strongly between $V = 14$ and $V = 17$, but should remain at acceptable levels for the detection of planets around solar-like stars. These calculations were based on simulated stellar brightness distributions, recording the number and the brightness of stars (other then the target star) that fall into the target's star aperture. The can be used to evaluate only the noise due to quiescent background sources. As about 10 % of dwarf stars show variability at some level (Borde et al. 2003 and references therein), crowding could in fact place more severe limits on permissible aperture sizes. Most background variables may however be detected due to the shifts they would cause in the position of the photometric centroid (Jenkins & Doyle 2003).

The current design is less than optimal for the observation of M, but also of K stars, as sky noise dominates in the magnitude range $V = 16$ to $V = 20$, where most K star with detectable habitable planets are expected to be found. Also, the fraction of these stars suffering from crowding will be high. A reduction in the size of the optical PSF is therefore needed, allowing the use of smaller photometric apertures. As a first step, the effect on the noise budget of reducing the aperture area by about a factor of ten, leading to a diameter of 3 arcsec (requiring a similarly reduced PSF of 1–2 arcsec FWHM), was evaluated. With this aperture size, using a conservative value of 21 mag/arcsec^2 for the sky brightness, sky-background dominates only for $V > 17$ (Fig. 4). Also, the fraction of crowded stars remains low throughout the

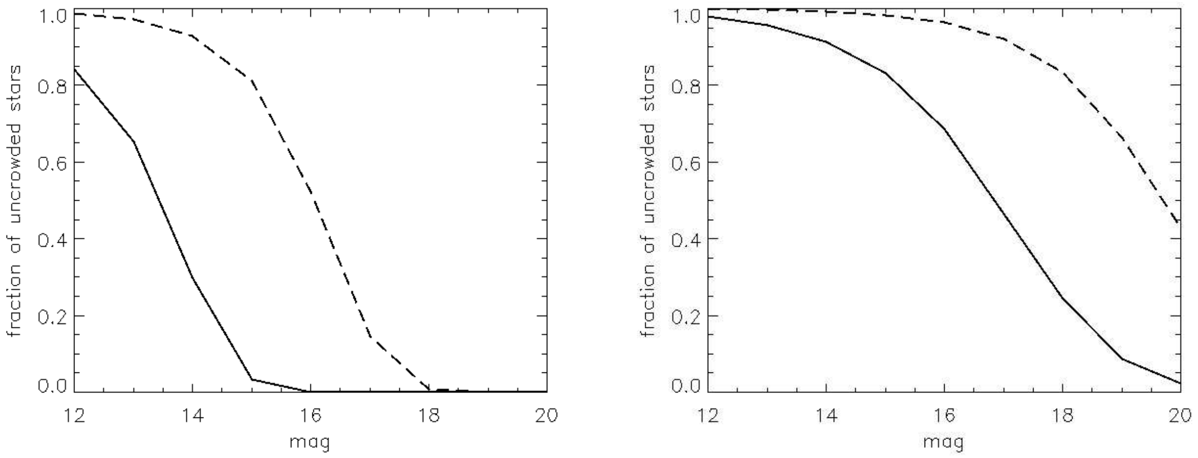

Figure 5. Evaluation of the level of crowding with 10 arcsec apertures (baseline). Solid line: fraction of uncrowded stars, where a star is defined as uncrowded if less then 1 % of the light within its aperture comes from background sources. Dashed line: idem, but a star is now defined as uncrowded if less then 10 % of light within its aperture comes from background sources. **Left panel:** *Estimate based on a field at low galactic latitude, where the stellar density corresponds to the field selected by the* Kepler *mission in Cygnus.* **Right panel:** *Estimate based on the average stellar density at 10° galactic latitude.*

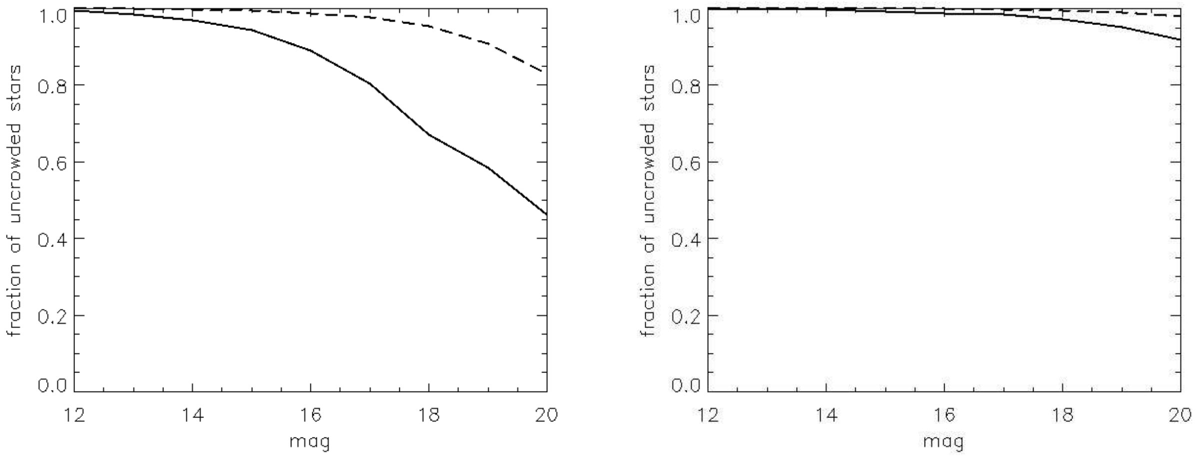

Figure 6. As Fig. 5, but assuming 3 arcsec apertures, optimised for M star observations. Crowding remains low in all cases.

entire range of sample magnitudes (Fig. 6). These advantages come at the expense of a saturation limit that is now shifted toward $V = 13$. Assuming a lower sky-brightness of 23 mag/arcsec^2, as has been observed at high ecliptic latitudes (Windhorst et al. 1994), photon noise will dominate even up to $V \approx 19$. The effect of a smaller PSF on the photometric precision is more complicated to evaluate and would need a dedicated study. It should be noted that the requirements on the photometric precision for the detection of habitable planets around low-mass stars are much less stringent than around solar-like stars, as transits are deeper and more frequent. This lower photometric precision requirement compensates for the effects of high stellar activity levels, which are more common in low-mass stars. For example, for $V = 17$ stars, activity would not become significant for the overall photometric precision – and hence for the detection of transits – for levels up to 500 ppm (compare to Fig. 4, right panel).

5. Conclusions and Recommendations for *Eddington*

In the previous section two aperture diameters (and corresponding PSF sizes) were evaluated: 10 arcsec (baseline), and 3 arcsec. The baseline set-up is optimised for the detection of Earth-like planets, of which only a small number can be expected. Even with this aperture, most of the detections will be planets around stars of less than solar mass (Horne 2002; Horne 2003). On the other hand, the use of the smaller aperture, which is optimised for

M stars, should lead to the detection of a sizable number of habitable planets – unless these are extremely rare. Earth-like planets around solar-like stars may or may not be detectable with the smaller aperture, the host stars stars being near the bright saturation limit and possibly suffering from a loss of absolute photometric precision due to the smaller PSF.

The detection of habitable planets around M stars would certainly be a well-motivated endeavour, as was argued in the first section, but such a detection may still not be considered as "valuable" as one of an Earth-alike around a solar-like star. Tidal locking, though not causing serious impediments to habitability in general, would also make these planets 'different' from Earth analogues. Selecting M stars as principal targets would also have implications on the selection of the observing field and on the mission design, requiring the evaluation of several further points:

- Sky-background would the limiting noise contribution for a larger portion of the range of magnitudes of interest, and the sky-brightness needs to be well established.
- The stellar sample would be much fainter. This makes preparation and follow-up observations more difficult, and impossible in some cases (e.g. radial velocity follow-up).
- As there will be more target stars in the field, consequences on telemetry and data processing capability need to be considered.
- Crowding may not be problematic based on the presented first-order estimations. These were based on galactic models which have low reliability for the very faint stars ($V > 22$) that would constitute the bulk of the background stars. Even for the faint target stars themselves, galactic models are not very reliable. Deep preparatory observations in potential fields could ascertain this.
- The scalability of transit detection algorithms needs to be evaluated. For example, are 40 events, each at the $2\,\sigma$ level (M star planet) as reliably detectable as 4 events at the $6\,\sigma$ level (as would be required for the detection of an Earth analogue)? For this kind of evaluation, the frequency dependence of the various noise characteristics for *Eddington* needs to be predicted and taken into account.

Considering the above points, an exclusive optimisation of *Eddington* for M stars may not be recommendable. A better strategy appears to be to optimise the mission to detect planets around mid-G ($V \approx 13$) to mid-M ($V \approx 19$) stars, by selection of an appropriate aperture (such as 5 arcsec diameter) and exposure time, together with a careful evaluation of the sky-brightness. A 5 arcsec aperture would correspond to an optimisation for mid-K stars. The expected rate of detection of habitable planets orbiting these stars is also higher than for G stars. Furthermore, the habitable zone of mid-K stars spans both sides of the tidal-locking distance-limit, which would lead to an interesting mix of detectable planets. An evaluation of the impact of stellar activity on transit detection for spectral types mid-F to mid-K (Aigrain et al. 2003) suggests that the effect of increase activity for K stars is more than compensated by the increase in transit depth and number of transits. Since *Eddington* will have a re-focusable PSF, other solutions for mission planning may also be considered, such as a separate block of observations specifically for M star targets. This is feasible, since a planet-finding phase dedicated to M star observations could be shorter than the 3 years required for solar-like targets, due to the short periodicity of their habitable planets (see Fig. 1). An interesting possibility may also be to take advantage of the "natural" degradation of the PSF between the centre of the field of view and its edges, thereby selecting different sample populations within the same field of view.

Beyond the recommendation to optimise *Eddington* "around" mid-K stars by using appropriate apertures and exposure times, this contribution is intended as a basis for further discussion toward an optimisation of the scientific return of *Eddington*'s planet finding mission.

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Appendix A: Discussion

J. Schneider: Since you are interested in habitable planets, I want to point out that habitable planets around M stars will not be detectable by Darwin because they are too close to their parent star and too faint. You mentioned that life on these planets may be anoxygenic, therefore undetectable by the oxygen/ozone signature. A vegetation-like signature (Briot et al. 2002; Arnold et al. 2002) is an alternative way to detect that kind of life.

T. Brown: Please let us not place too much emphasis on questions of habitability. The first question is: what is the nature of the population of small planets around distant stars.

G. Handler: A recent observing programme at SAAO tried to establish very red M type standard stars for photometry. One of the results was that almost every M star was variable on a level of several hundreds of magnitudes. This severely offsets the detection probability of planets despite the larger number of transits and (deeper transits caused by) smaller stars.

H. Deeg: This certainly has to be considered. For transit detection only variability on time-scales of a few hours is decisive, however, and fairly high levels of activity are indeed tolerable (see Fig. 4 and caption to its right panel). Most M star activity results from flare-like events, which occur on shorter time-scales and are relatively well recognisable and removable from a light curve. Optimisation of *Eddington* for K stars, while including early M stars, as was finally recommended, should minimise problems due to variability.