EDDINGTON'S PLANET FINDING CAPABILITIES

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Abstract

The capabilities of Eddington for the detection and analysis of extrasolar planets are outlined. The primary goal of the PF (Planet finding) part of the mission is the detection of planets that are Earth like - which limits their size to less then 3 Earth Radii - and which are potentially habitable - which limits their temperature *or* their orbital distance and period. Secondary goals will be the detection of larger planets and their analysis.

For evaluations, stellar light-curves from Eddington were simulated, and artificial transits were included in a subset. These curves then served as the base for detectability tests, giving us an outline of the stellar-size versus planet-size versus planet-temperature parameter space in which Eddington may perform reliable detections. For stars smaller then about G5V, and brighter then $m_V = 16$, Eddington will detect any transiting planets with minimum sizes of 1-2.5 Earth radii.

As Eddington will survey several hundred-thousands of stars for transits, a significant number of Earth-like planets would be detected, provided that the fraction of stars with such planets is not a small number. Also, there will be detections of large numbers of giant planets through transits, as well as a complete survey of Hot Giant planets, as these can be detected by reflected light - even if they are not causing transits.

Key words: Planets: exoplanets – transits

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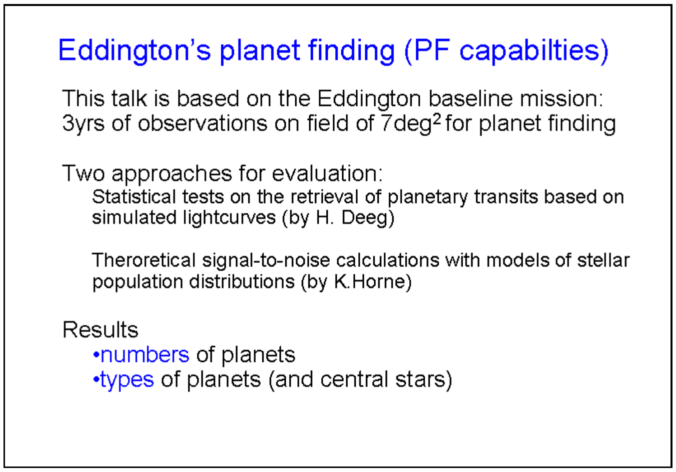
1. Introduction

In the following, an overview is given about the capabilities of Eddington towards the detection of extrasolar planets. It is given in the form of an adaptation of the slides presented at the meeting in Cordoba, interspersed with some additional comments. For a more technical description of the planet finding (PF) capabilities of Eddington, we refer to the Eddington Assessment Study Report (Favata et al., 2000), sections 7.1, 7.3 and Appendix B. Also of interest is section 6.2, which describes the requirements that these capabilities pose onto the mission design. Also, two previous conference proceedings describing Eddington PF capabilities are given by Deeg et al. (2000a, 2000b).



Eddington's planet finding (PF capabilties)

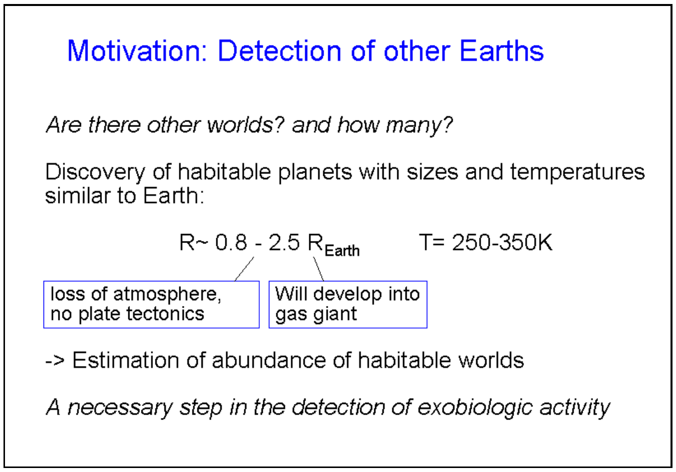
This talk is based on the Eddington baseline mission:
3yrs of observations on field of 7deg^2 for planet finding

Two approaches for evaluation:
Statistical tests on the retrieval of planetary transits based on simulated lightcurves (by H. Deeg)

Theroretical signal-to-noise calculations with models of stellar population distributions (by K.Horne)

Results
- numbers of planets
- types of planets (and central stars)

Figure 1.



Motivation: Detection of other Earths

Are there other worlds? and how many?

Discovery of habitable planets with sizes and temperatures similar to Earth:

R~ 0.8 - 2.5 R_{Earth} T= 250-350K

loss of atmosphere, no plate tectonics

Will develop into gas giant

-> Estimation of abundance of habitable worlds

A necessary step in the detection of exobiologic activity

Figure 2.

Results of the studies presented here assume the Eddington baseline mission (Fig. 1), as described in the Assessment Study Report: a telescope of about 0.6m^2 effective mirror area, that will observe a single stellar field of several hundred thousand stars for 3 years, with a single-color CCD camera with a field of view of about 7 deg^2. This does not exclude that Eddington's PF mission will undergo further changes; the discussion of alternative mission concepts is however outside of the scope of this contribution. The motivation for the current baseline mis-

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sion, and its primary goal, is the detection of habitable or Earth-like planets (Fig. 2), where 'Earth-like' refers to both a planet's size and temperature.

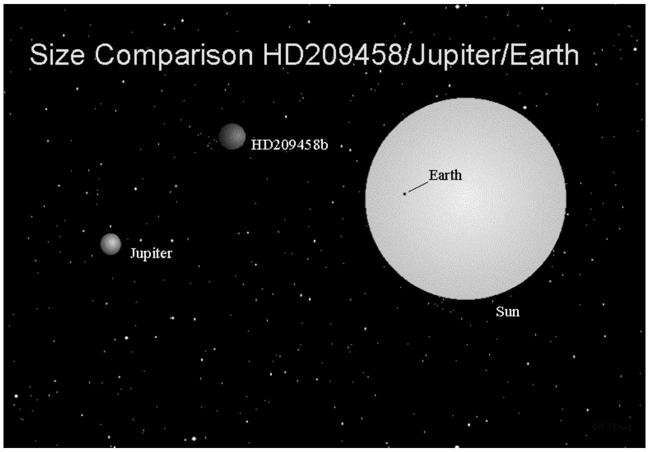
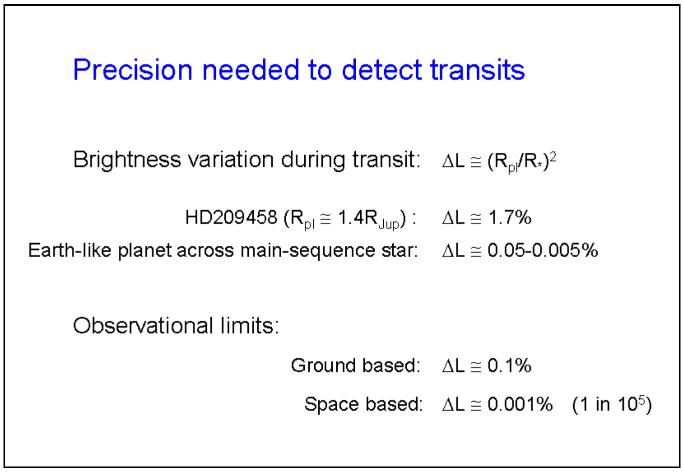


Figure 3.



Precision needed to detect transits

Brightness variation during transit: $\Delta L \cong (R_{pl}/R_*)^2$

HD209458 ($R_{pl} \cong 1.4R_{Jup}$) : $\Delta L \cong 1.7\%$
Earth-like planet across main-sequence star: $\Delta L \cong 0.05\text{-}0.005\%$

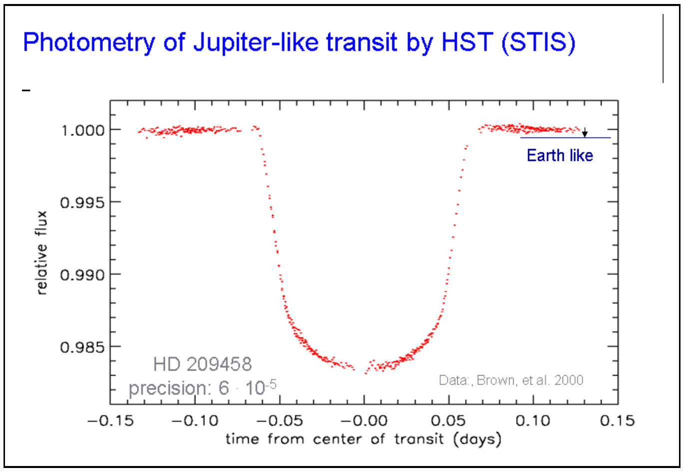
Observational limits:
Ground based: $\Delta L \cong 0.1\%$
Space based: $\Delta L \cong 0.001\%$ (1 in 10^5)

Figure 4.

2. WHY GO TO SPACE

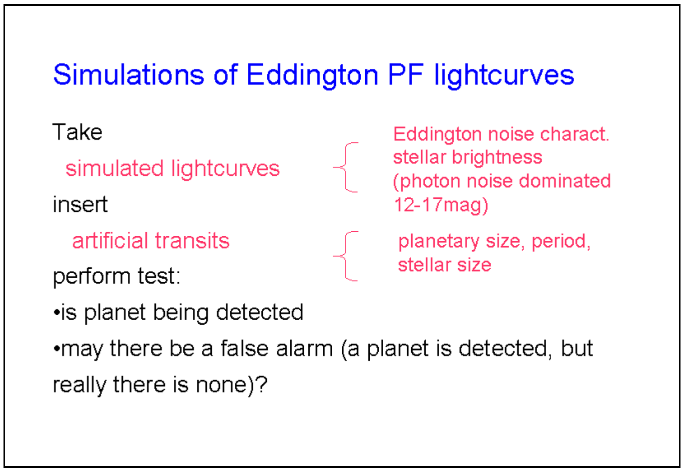
For the planet around the star HD209458, transits where discovered in late 1999, which cause a brightness drop of 1.7%. The difference in size between that planet (shown in Fig. 3) and the Earth is however considerable, and so would be the magnitude of the brightness variations caused during transits. While detecting the HD209458 transit is within the reach of advanced amateur astronomers, observations of transits of terrestrial planets around solar-like stars are beyond the limits of ground-based observations (Fig. 4).

Observations undertaken with the STIS spectrograph on board of the HST (Brown et al., 2001) show the potential of space-based transit observations (Fig. 5 - horizontal line is for large terrestrials with 3 R_{Earth}). Even though they were done with a non-optimized instrument like STIS, it was demonstrated that the precision needed for the detection of transits of Earth-like planets is achievable from space.



Photometry of Jupiter-like transit by HST (STIS)

Figure 5.



Simulations of Eddington PF lightcurves

Take
simulated lightcurves { Eddington noise charact. stellar brightness (photon noise dominated 12-17mag)
insert
artificial transits { planetary size, period, stellar size
perform test:
•is planet being detected
•may there be a false alarm (a planet is detected, but really there is none)?

Figure 6.

3. EVALUATION OF DETECTION LIMITS OF EDDINGTON

Limits of detection capabilities where derived from simulations of stellar light-curves as they would be delivered by Eddington. Two sets of curves were created (Fig. 6): light-curves with simulated noise only, and light-curves with added transits of uniform characteristics (such as planet size and period). Detection tests were then performed, that return 'detection coefficients' c, which are numbers that describe the likelihood that a transit is present in a light-curve. When repeating such light-curve simulations and detection tests in large numbers ($N=10^{4-5}$), values of c for 'noise only' light-curves (labeled c_n) and for curves

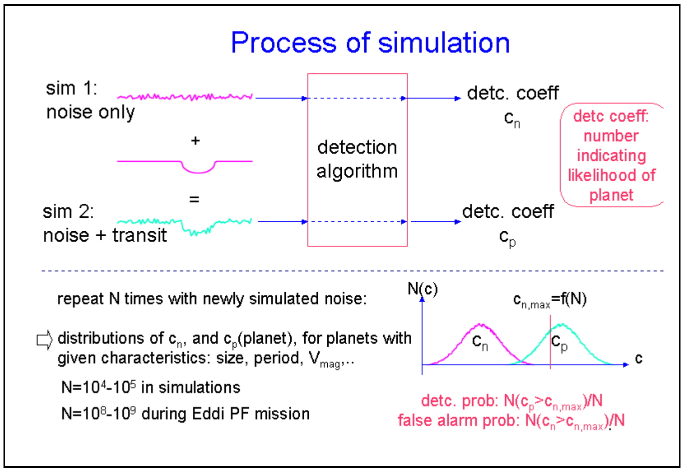


Figure 7.

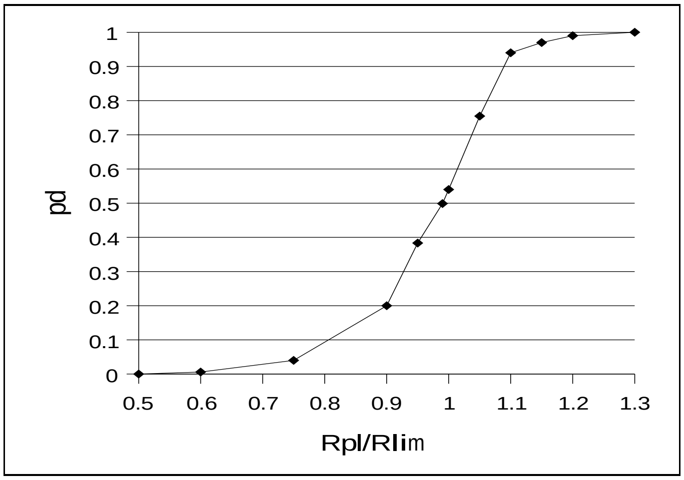


Figure 8. Detection probability against relative planet size

with transits (labeled c_p) form two Gaussian-shaped distributions (Fig. 7). The amount of separation between these two distributions indicates a planet's detectability, and is governed by the S/N and duration of a transit signal, the number of individual transits in the light-curve, and by the quality of the detection algorithm. In order to avoid (or minimize) false alarms, the lowest acceptable c value that constitutes a detection has to be larger then the highest expected c value found in noise-only light-curves, $c_{n,\max}$. If a significant fraction of light-curves *with* transits results in c values lower then $c_{n,\max}$, detection probabilities, given by the fraction $p_d = N(c_p > c_{n,\max})/N(c_p)$, may become low. In further results that are shown, minimum detection probabilities of $p_d \geq 50\%$ are used. As shown in Fig. 8, p_d is a steep function of planet size, and $p_d > 90\%$ is achieved for planets only 1.1 times larger than those at the 50% limit. A further limit for a 'true' planet detection is the presence of at least 3 individual transits during observations. During the 3 year observations of Eddington, this limits planet detections to a maximum orbital period of about one year (Somewhat longer periods may also be detected with 3 transits, depending on the epoch of the transit. Detection probabilities are however going towards zero as periods approach 1.5 years.)

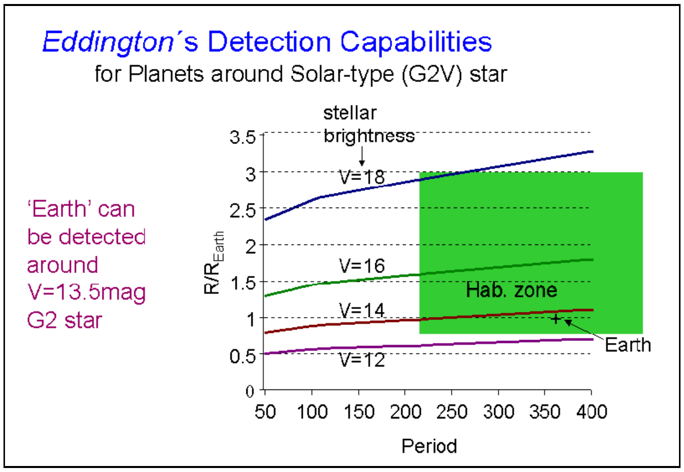


Figure 9.

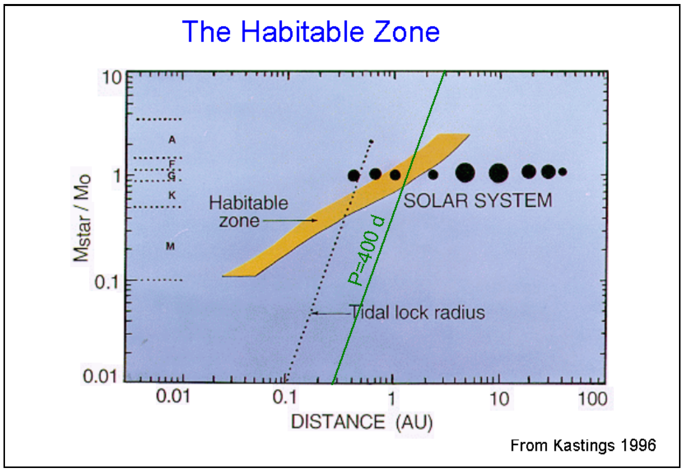
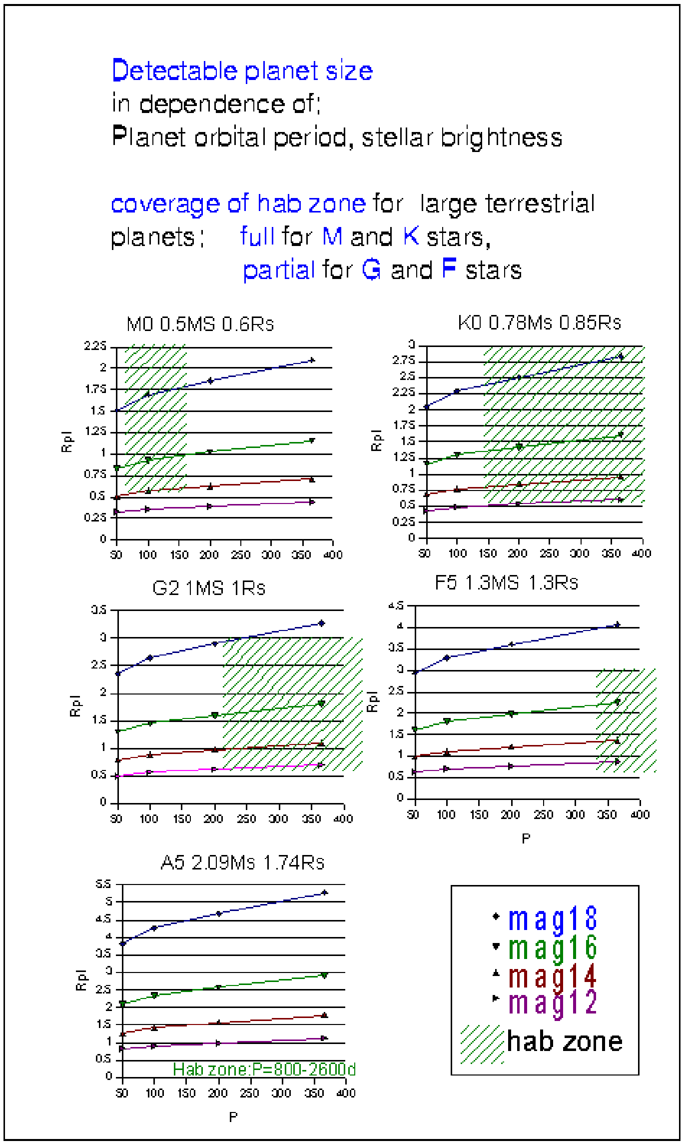


Figure 10.

In Fig. 9, detectable planet sizes are shown in dependence of the central star's brightness and the orbital period (which affects the transit signal through the number of transits that can be detected). For a G2 star, Eddington can cover a large amount of the parameter space that represents the habitable zone (Fig. 10) in terms of orbital period (or temperature) and planet size. A minimum brightness of V≈ 13.5 is needed for the detection of an exact Earth equivalent. For smaller stars (K and M), coverage of the habitable zone is even more complete (Fig. 11), whereas only the 'hotter' end of habitable zones is accessible around F stars.

A second approach (Fig. 12) towards the evaluation of detection capabilities was undertaken by K. Horne, based on calculating the condition that the transit signal needs

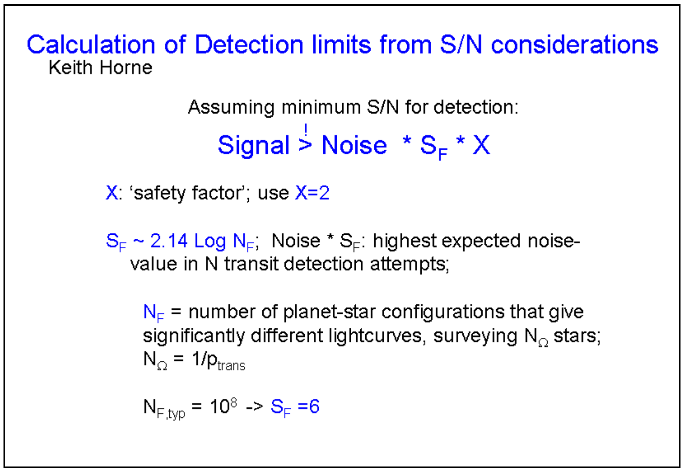


Detectable planet size
in dependence of:
Planet orbital period, stellar brightness

coverage of hab zone for large terrestrial planets: full for M and K stars, partial for G and F stars

Figure 11. The habitable zone is indicated by the hatched area

to be larger then then the highest expected noise in all N differentiable transit detection attempt needed for the encounter of one planet (a number on the the order of $N = 10^{8-9}$), multiplied by a 'safety factor' X. Fig. 13 shows transit light-curves folded by orbital period for a $1R_{\rm Earth}$ planet with 300K temperature, against varying stellar diameters and brightnesses. The parameter-space covered by the requirement X=2 agrees very well with results from the detection simulations (Fig. 6-11) and - again - the detection of a true Earth equivalent needs to take place around a star with at least V≈ 13.5.



Calculation of Detection limits from S/N considerations
Keith Horne

Assuming minimum S/N for detection:

$$\text{Signal} \overset{!}{>} \text{Noise} * S_F * X$$

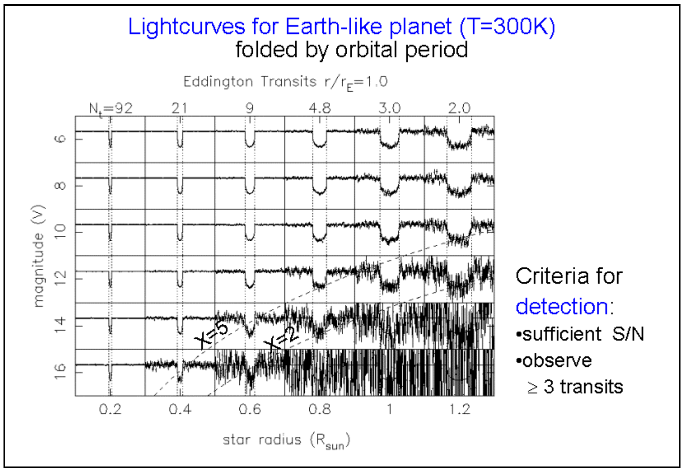
X: 'safety factor'; use X=2

$S_F \sim 2.14 \text{ Log } N_F$; Noise * S_F: highest expected noise-value in N transit detection attempts;

N_F = number of planet-star configurations that give significantly different lightcurves, surveying N_Ω stars; $N_\Omega = 1/p_{\rm trans}$

$N_{F,\rm typ} = 10^8$ -> $S_F = 6$

Figure 12.



Lightcurves for Earth-like planet (T=300K)
folded by orbital period

Criteria for detection:
- sufficient S/N
- observe ≥ 3 transits

Figure 13.

4. Numbers and characteristics of detected planets

For the derivation of the numbers of planets that will be detected, and their characteristics, the detection *capabilities* of Eddington need to be folded over the stellar sample that can be surveyed. The two principal features of that sample are: fainter stars dominate in numbers any brightness limited stellar sample, and low mass main-sequence stars are becoming increasingly dominant with decreasing brightness (Fig. 14). Eddington will survey in significant numbers (and with sufficient precision) stars in the magnitude range V=14-19; the sample will hence be dominated by solar-like stars of spectral classes F,G and K. Estimations of the stellar sample depend to a large extent on the Galaxy model used and the external assumptions (especially extinction) that are being fed in. Their results can to some degree be verified through comparisons with deep stellar catalogues, especially the USNO2 with a magnitude limit of about V=19. Detailed observations to characterize the stellar sample will however be needed for any field that is a serious candidate for the PF survey.

More uncertain is still the abundance of detectable planets or planetary systems. Except for Hot Giant planets, no first order estimates exist. Abundances of solar-system equivalent planets are still completely unknown

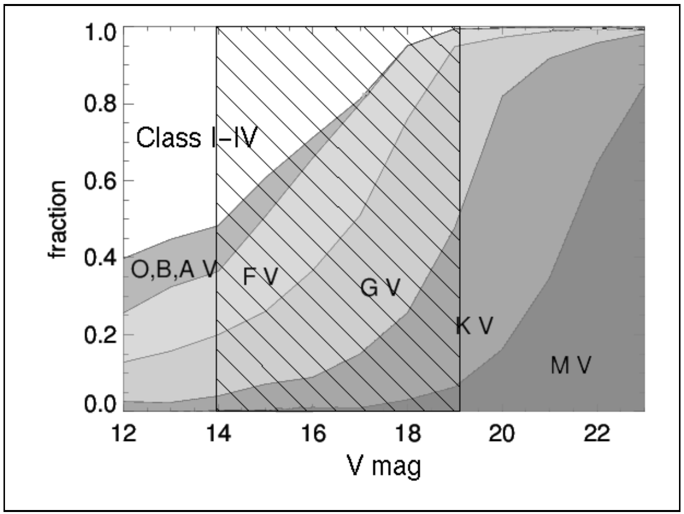
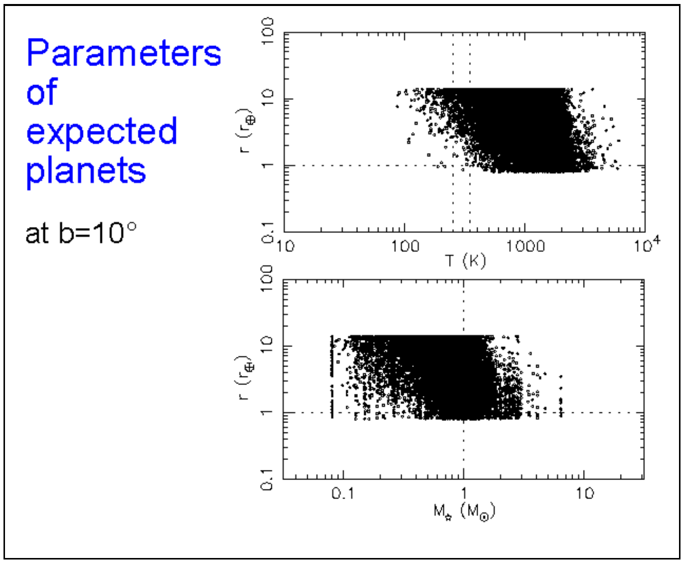


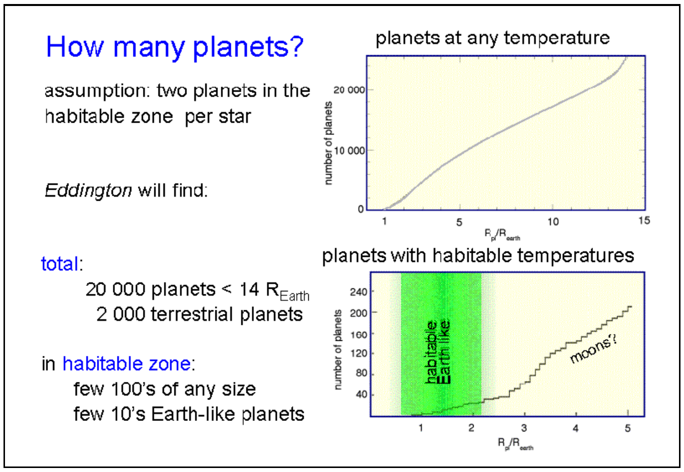
Figure 14. Stellar types against brightness, for a typical field at b=5 deg (simulation from Besancon Galaxy Model). The hatched region indicates the magnitude range of the Eddington PF sample.



Parameters of expected planets

at b=10°

Figure 15. Upper panel: planet radius against temperature; lower panel: planet radius against stellar mass



How many planets?

assumption: two planets in the habitable zone per star

Eddington will find:

total:

20 000 planets < 14 R_{Earth}

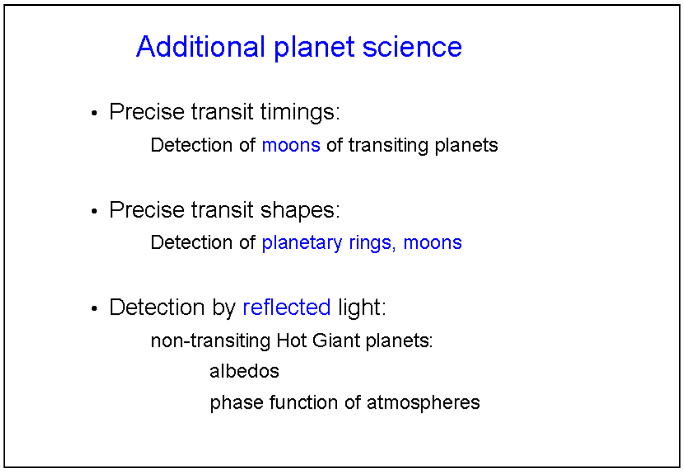
2 000 terrestrial planets

in habitable zone:

few 100's of any size

few 10's Earth-like planets

Figure 16. In the lower panel, the size-range of habitable planets from 0.7 to 2.5 Earth radii is indicated.



Additional planet science

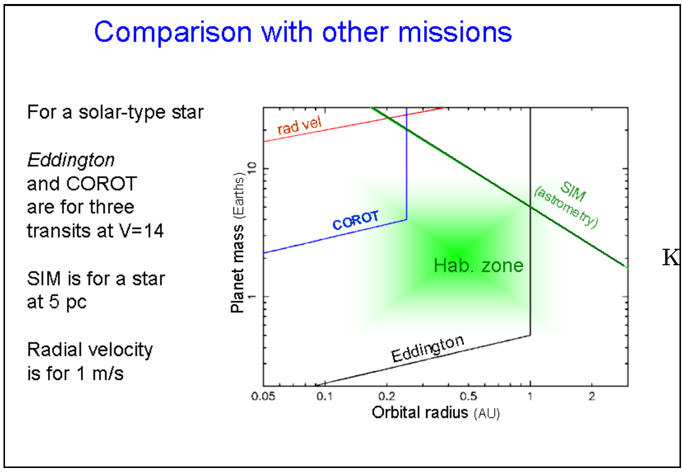
- Precise transit timings:
  Detection of moons of transiting planets
- Precise transit shapes:
  Detection of planetary rings, moons
- Detection by reflected light:
  non-transiting Hot Giant planets:
    albedos
    phase function of atmospheres

Figure 17.

(though true Jupiter and Saturn equivalents are expected to be discovered from radial velocity surveys in the next years), and Solar-System equivalence assumptions were used, where the probability for planet presence is scaled with $a^{-1}Mr^{-1.5}$ (a: orb. half-axis, M: planet mass, r: planet radius). The discovery of thousands of planets is expected, with a sample dominated by large and hot planets (Fig. 15). Provided that the fraction of stars with planets is not a small one, considerable numbers of planets will be detected within the habitable zone (where larger planets might also harbor life on terrestrial sized moons), among them a few tens of terrestrial-sized planets - potential harbors for life (Fig. 16). Besides the pure detection of transiting planets - allowing the derivation of primary planet parameters as size, orbital period, distance, inclination and temperature estimation, further knowledge on exoplanets (Fig. 17) may be gained from secondary effects such as transit-timing, or an analysis of a transit's shape, both possible indicator for third bodies. Also, non-transiting Hot Giants may be detected through their reflected light as they change phases (similar to the Moon) and brightness in their orbit around their central star. This may lead to they detection of large numbers of these bodies.

5. The Eddington Exoplanet mission in perspective

In comparison with other missions that are currently being developed (Fig. 18) and which can survey only 'edges' of solar-type stars' habitable zones, Eddington will extend this coverage (also in terms of planet size) towards a large fraction of the available parameter-space and give



Comparison with other missions

For a solar-type star

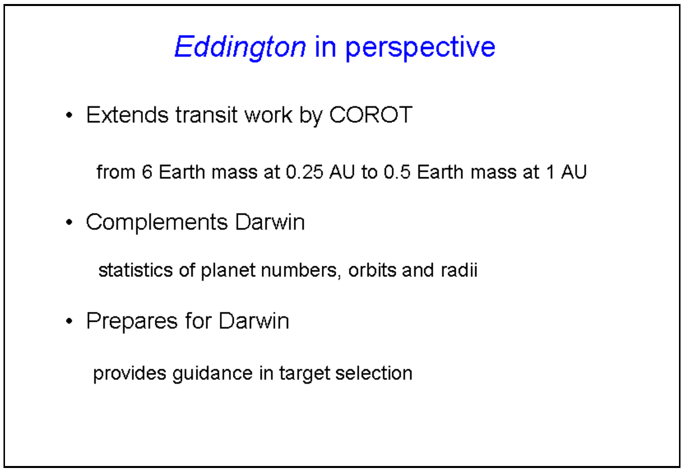
Eddington and COROT are for three transits at V=14

SIM is for a star at 5 pc

Radial velocity is for 1 m/s

Figure 18.

a profound survey of habitable planets. Eddington will also serve as an important intermediate step between near-term missions like COROT - which is expected to detect many short-periodic, hot planets - and very advanced concepts like Darwin, which will should lead to the detailed characterizations of entire solar systems (Fig. 19).



Eddington in perspective

- Extends transit work by COROT

  from 6 Earth mass at 0.25 AU to 0.5 Earth mass at 1 AU

- Complements Darwin

  statistics of planet numbers, orbits and radii

- Prepares for Darwin

  provides guidance in target selection

Figure 19.

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