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DETECTING EARTH-URANUS CLASS PLANETS WITH THE SPACE MISSION *COROT*

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ABSTRACT

The space mission *COROT* can be viewed as a DARWIN precursor, since it will contribute to the pre-Darwin effort with its dedicated exoplanets program. *COROT* will survey more than 50 thousands stars, each one during five months, in order to detect transits of planets. Despite of the modest size of the telescope, the photon-noise limited performances may lead to the detection of several tens of "hot Jupiters" and, more important, of a few planets of the Earth-Uranus class, i.e. with a size of typically 1.5 to 4 Earth radius. In the basic mode of operation (at least 3 detected transits), only planets with a short orbital period, and thus rather "hot" ones (T = 600K), should be discovered. However, one of the *COROT*'s features is its capability to provide a wavelength dependant information, thanks to a prism in the optical path. Because this information will permit to solve ambiguities in the case where twin or even unique transits are detected, *planets in the habitable zone could be detected.* The paper describe the goal of the mission, the instrument and the expected performances. The case of small planets (Earth-Uranus class) in the habitable zone is especially examined.

Key words: Exoplanets ; Space mission ; Photometry ; Transit ; Darwin and Astronomy

1. INTRODUCTION

A sensible approach of the search and study of extrasolar planets around main sequence stars is: *a)* searching for Giant exoplanets, *b)* searching for Telluric ones; *c)* spectroscopically analyzing them, with an emphasis on Earth-type ones.

The first step has been made with the discovery of 51 Peg b in 1995 (Mayor, Queloz, 1995). In fact, it has been preceded by a photometric observation by Hipparcos of a planetary transit in front of the star HD 209458, several years before, but recognized as such only recently (Robichon & Arenou, 1999). Since this first discovery, there has been a dramatic increase of the number of planets of Jupiter's class detected by means of radial velocity (RV) technique. However, presently we miss an unbiased statistics of these planets. Step two is accessible to the *COROT* mission *only* (or to similar ones, as Kepler in the US but which is not approved). The third step is the main goal of DARWIN, possibly the most ambitious mission ever studied by ESA.

Concerning giant exo-planets, the GAIA proposal for the 2009 Corner Stone would detect about 50 000 giant planets du to the huge number of stars which are studied by astrometry, at the 10 micro-arcsec level. It should provide an excellent statistics on Giant planets but cannot detect Earth-like ones because the astrometric signature produced by an earth on a sun at 10 pc has a total amplitude 2 $\delta\theta$ = 0.6 micro-arcsec, 16 times lower than the GAIA accuracy. The Radial Velocity produced by an earth on a sun has a total amplitude 2 δV = 20 cm s^{-1}, i.e. 5 times the best expected accuracy by this techniques. Further improvements seem not possible due to the intrisic noise generated by the stellar activity, which put earths out of reach. Microlensing will likely detect giant exoplanets but it is most doubtful that it can detect any telluric ones, at least in the foreseen future. Therefore, *none* of these techniques can detect Earth-like planets.

COROT, in its exoplanetary programme (Rouan et al., 1999), will search for planetary transits in front of stars by performing stellar photometry with an accuracy which is not accessible from the ground. *COROT* will be able to detect Earth-size planets which are close to their stars (as Mercury or closer) and planets with 1.5 $R_\oplus$ in the Habitable Zone (a = 0.95 to 1.35 AU).

Giant planets transits are detectable from the Ground, as it has been recently demonstrated in front of the star HD209458 (Charbonneau et al., 1999), but not earth-like ones. As a consequence, *COROT* is the *only* photometric mission that can detect these objects, before DARWIN.

Presently, we do not know the statistical distribution of earth-like exoplanets as function of their size. *COROT* could demonstrate the "existence theorem". Now, this piece of information is crucial for DARWIN whose main goal is to perform the spectroscopy of such objets.

If this existence was not proven, we must use the first

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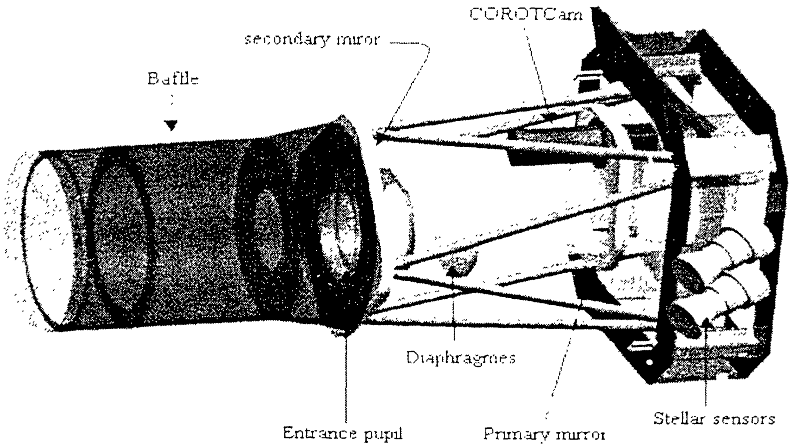

Figure 1. The *COROT* satellite. One can see the the wide-field telescope, made of two off-axis parabola and a refractive objective, as well as the long baffle and electronics housing.

phase of the DARWIN mission to searching for earth-like planets around nearby stars and produce the catalogue of objects to be studied. Now, if *COROT* detect planets with R $\approx$ 1.5 $R_\oplus$, it would allow a much better optimized observation strategy. This results from the dependence of DARWIN integration time, to obtain a given SNR, upon the the planetary radius: $t_{integration} = kR_{pl}^4$, where k is a constant when other parameters are fixed.

It implies that if DARWIN wants to search for planets around stars which are further away than our nearest neighbourhood, say at 30 pc, the time required for the detection of an Earth-size object is of the order of 10 days which is probably prohibitive for studying a single star, the more as the time required for spectroscopy would be still significantly longer. If we know that super-earths exist with radius three times that of the Earth, the detection time would decrease down to 3 hours and it becomes worth searching for such objects.

COROT will not provide a target list for DARWIN because it will detect earth-type planets with orbit almost edge on, the worst case in terms of the exozodiacal light background. As a consequence, it must monitor a large number of stars in a given field of view (few square degrees) and therefore distant ones, typically at 500 pc, while DARWIN will concentrate on the nearest and brightest objects. But if we make the plausible assumption that the planet distribution is the same in the solar neighbourhood and at 500 pc, we will know the fraction of stars that have planets of a given size in those which are accessible to DARWIN, a most valuable piece of information for optimizing the searching procedure.

2. The transit method

The transit method (e.g. Schneider, 1996) has the unique advantage to potentially detect *Earth-type planets around solar-type stars*, since the amplitude of the variation – typically of $(R_\oplus/R_\odot)^2 \approx 10^{-4}$ – is within reach of a photometric experiment in space, monitoring thousands of stars continuously.

The specific characters of the transit method are :*i)* an amplitude of flux variation, $\Delta F/F = (R_{pl}/R_{star})^2$ rather easily detectable : for the Earth in front of the Sun (G2 star) : $\Delta F/F = 0.8\ 10^{-4}$, while for a Jupiter in front of a M0V star, $\Delta F/F = 2.5\ 10^{-2}$; *ii)* duration of the transit event $\tau = T_{orbit} R_{star}/(\pi R_{orbit})$, i.e. typically 4 to 15 hours ; *iii)* planet, star and Earth must be almost aligned for the transit to be seen, the probability being given by D_{star}/D_{orbit}, i.e. about 0.5% of planets at 1 AU properly aligned ; this fraction amounts to 10 % in the case of the so-called *hot Jupiters*, i.e. planets orbiting very closely to the star ; *iv)* for a detection to be confirmed, one generally requires that 3 transits, equally spaced in time, are detected ; we show in the following that this condition can be relaxed if a multi-colour information becomes available; *v)* the measured quantities are the orbital period and $\Delta F/F$; the first one gives the orbit radius, thus an estimate of the temperature of the planet (apart from albedo and atmosphere green house effect), the star spectral type being known, while the second one gives the *size of the planet, a unique piece of information.*

In brief, the transit method is favored by a cool but apparently bright star (smaller radius makes $\Delta F/F$ larger and many photons a better S/N) and a big planet on a close orbit: this is not exactly a set of conditions that favours detection of earth-like planets in the habitable zone of a sun type star, however *COROT* could have the capability to find a handful of them, provided that they are frequent enough.

3. The Exoplanet program in *COROT*

3.1. The mission and instrumental set-up

COROT (Baglin, 1998) was selected within the frame

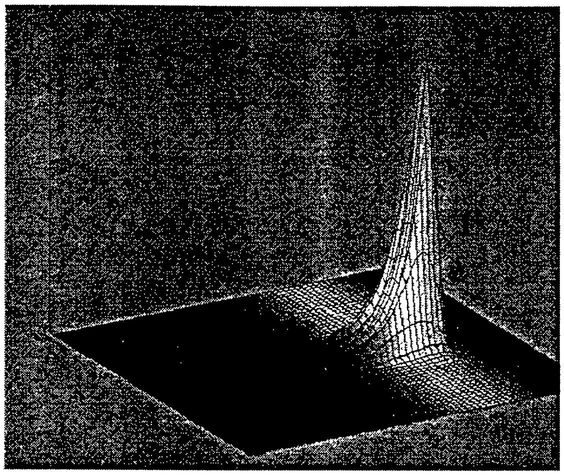

Figure 2. The PSF on the exoplanets channel of *COROT*. A pair of prisms, mounted head to toe, provides a dispersion in one direction at a low spectral resolution, and also contribute, through astigmatism, to spread the light in the perpendicular direction for a better photometry.

of the Small Mission Program of the French Space Agency CNES. It will cost typically 55 M$. Partners are : CNES, LAS (Marseille), DESPA (Meudon), IAS (Orsay), Austria and ESTEC. ESA, Italy and Belgium will also likely join the collaboration soon. More modest than the similar US project *Kepler* (Koch et al., 1996), *COROT* is however, today, the only selected mission. The main characteristic of *COROT* is to perform high accuracy photometry on a wide field. This will permit to fulfil the requirements of the two main scientific objectives of the mission: a) to measure stellar pulsations on a small set of stars and b) to detect exoplanets. The two programs share a same instrument, featuring a 25 cm telescope without obscuration (2 off-axis parabola plus a dioptric objective) and 4 cooled (-40 Celsius) CCD 2048 × 2048 from EEV, with two devices per program. The field of view of the 2 exoplanets CCDs is $3.5\ (^\circ)^2$. The platform *Proteus* provides a pointing stability of 0.15 arcsec. Fig. 1 depicts the telescope on its platform.

The orbit of *COROT* is pseudo-polar, quasi-inertial at an altitude of 850 km. During the 2.5 years mission, five fields will be observed continuously, each during 150 days. Launch, using a Russian *Rockot* or a rocket from India, is planned in 2004.

The goal of the Exoplanets program, will be achieved by monitoring continuously 6000 to 12000 stars in each field, with m_V = 11 to 16.5, at rather low galactic latitudes (b_{II} = 10-15°). Each exposure will be 32 sec. In order to cope with the data transmission rate of 900 Mbits per day, data will be co-added on-board during periods of 15 minutes, before being down-loaded. Time sampling will be improved, down to 1 minute, for certain stars where an event will have been previously detected, so that one will be able to measure – thanks to the small variations of the period – the effects of satellites around the planet and of other (non- occulting) planets that will produce a reflex motion on the star (Sartoretti & Schneider, 1998). Scattered light from the Earth limb will be maintained at a low level thanks to an afocal telescope design and a long baffle. Zodiacal light level is important but is stable and will dominate the noise figure. The expected performances are such that a *big Earth* ($R_{pl}/R_\oplus = 1.6$) should be detected against a $m_V = 14$ star, with a S/N = 4, on transit events of 10 hours duration. In the basic mode (three transits detected), only planets with an orbital period shorter than 50 days will be unambiguously detected, i.e. rather "hot" planets (T > 600 K). The chromatic mode was proposed to partly overcome this limit.

3.2. The multi-colour information

In principle a transit event should appear as a characteristic downward slot in the light curve, and usually be distinguished from a presumably more chaotic stellar fluctuation. However, at a modest Signal to Noise ratio, some stellar fluctuations could mimic a transit. A color information will help strongly to remove the ambiguity (Rosenblatt, 1971). Transits are essentially achromatic (geometric effect), while intrinsic stellar fluctuations are highly chromatic (temperature variations on the stellar surface) as shown by the Virgo experiment on-board Soho ($[\Delta F/F]_{400nm} = 2.4 \times [\Delta F/F]_{800nm}$). A second important advantage of a chromatic information is that ambiguity can be removed in the case of a binary system where a Jupiter-type transit around the faint component can mimic a Earth-type event around the brightest star. The confusion between the two types of events will be the most critical when the two stars will have typically 5 magnitudes difference in brightness : but in that case their temperatures and colors will be very different and the relative variations in the blue and in the red should give the proper answer. This is a real problem if one considers that 70 % of the stars belong to a binary system.

In order to obtain this chromatic information, a small bi-prism is put a few centimeters above the exoplanet CCDs and produces an on-axis mini-spectrum at each star image. Fig. 2 illustrates how the PSF obtained by introducing a pair of prisms, head to toe, in the beam can provide a multi-colour photometry. Astimagtism generated by the prisms is ex-

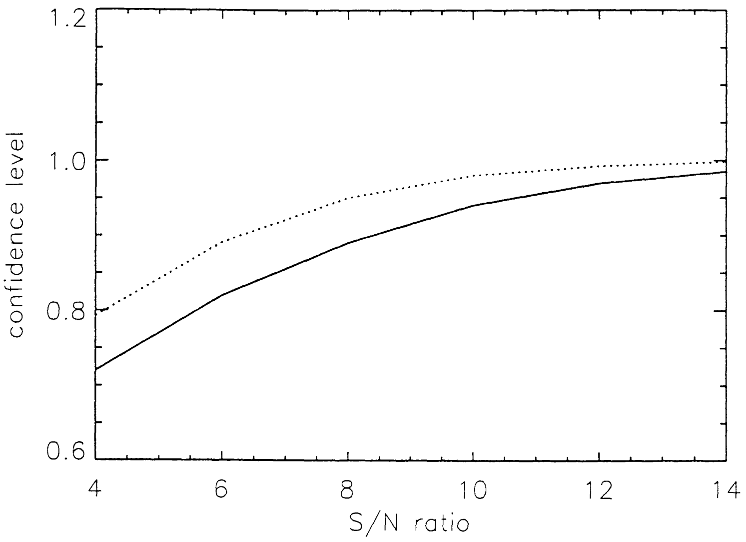

Figure 3. Plot of the confidence level of the discrimination – thanks to the chromatic information – between actual transits and other photometric events, versus S/B of total flux; solid line: a single transit with respect to a stellar fluctuation; dotted line: a Jupiter's transit on a M5 star with respect to a Earth's transit on a K5 star (case of binary stars) .

ploited to spread the image perpendicular to the dispersion while keeping a sufficient spectral resolution. Summing pixels on defined ranges of this spectrum gives red, green and blue light curves.

A proper combination of the different colour light curves will be used as a discrimination function. It will tell us if a given event is rather a transit and, in binary systems, if it is due to a Earth-type or to a Jupiter-type planet. We have shown (Bordé et al., 2000) that a linear combination of three colours is a powerful discrimination function, when the weight are properly chosen. Fig. 3 shows the degrees of confidence on the identification of a transit event according to the S/N ratio on the integrated (white) flux, assuming the chromaticity of the sun for stellar fluctuations ; as one expects, the higher the S/N, the better the degree of confidence of this identification.

One can easily verify that small errors in pointing generally do not produce a large error on the global photometry of one star : essentially all photoelectrons are collected; this is no longer true as regards the color information, because then there is a fixed boundary on the CCD that defines the different colors and a shift of the *spectrum* will transfer signal across this border from one color to the other, introducing a large uncertainty when the co-addition is done on periods of 15 minutes. In order to limit this effect, it has been decided that shift-and-add of the signal will be performed on-board, using fast algorithms.

An important consequence of this discrimination by the colors is that dual events, or even unique ones, could be clearly identified as transit, relaxing the condition on a short orbital period of the planet and thus on its distance to the star. This means in particular that *COROT could detect planets in the habitable zone.*

3.3. Sources of noise, performances

Thorough numerical simulations of the optical setup, of the platform pointing, as well as laboratory tests on CCD allowed us to identify the perturbations and the limitations in photometric performances. This is summarized in the following: – Pointing errors coupled to non-uniformity of the CCD response (flat-field) : this should not be a limit down to $m_V = 17$, thanks to the excellent pointing performances of the Proteus platform (0.15 arcsec rms). This make practically un-useful a fine flat-field measurement.
– Defocusing at an orbital period, due to small distorsions of the telescope structure when thermal fluctuations are generated by sun eclipses along the orbit. This may become a noise larger than the photon noise and will require ground post-processing. To reduce this orbital effect, the integration time on one orbit is adjusted to be as close as possible from the actual orbital period : averaging blocks of data on this period will supress the corresponding component of the frequency spectrum.
– Spikes in pointing due to de-saturation of the inertia wheels (coupling on the Earth magnetic field) : this will occur during periods of 20s each 40-120 min, i.e. a small fraction of the observing time. No observation will be performed during those periods.
– Scattered light from the Earth limb : a level of 0.1 $e^- s^{-1}$ pixel^{-1} is expected from simulation with the a-focal telescope design and a long baffle ; even if modulated, this will give a small contribution to the

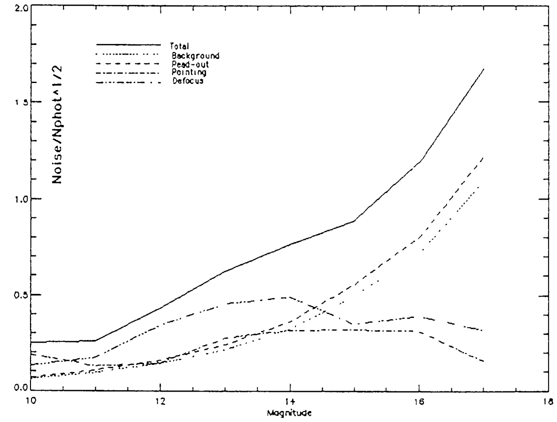

Figure 4. Uncertainties introduced by the different sources of noise, with respect to the photon noise, as a function of the stellar magnitude.

signal and to the noise.
- Zodiacal light : using data from James et al. (1997), we evaluate a maximum contribution to the signal of 10 e- s^{-1} $pixel^{-1}$; this level is important since its statistical noise will be slightly larger than the read-out noise, but it is a stable flux at the time scale of a transit and its dependence on latitude and longitude within the solar system is known.
- Particles : especially when crossing the South Atlantic Anomaly, the number of glitches due to particles will increase drastically (factor 10^5) and no observations will be acquired during $\approx$ 5 min.
- Nearby variable stars : if a faint variable star is within the photometric diaphragm of one of the target star, its fluctuation may mimic a transit. We have modeled this effect using actual stellar field and found that it should happen in less than 5% of cases, assuming 30 % of variable stars with 5 % relative variation, a very pessimistic case compared to Hipparcos results (Grenon, 1999).

Fig. 4 summarizes for the proper range of stellar magnitudes in *COROT*, the estimated role of the different sources of noise, in terms of the ratio of the S/N to the photon noise.

4. Expectation on the number of planets *COROT* could detect

Using models of stellar populations in the Galaxy (Bienaymé, Robin & Creze, 1987), and the performances expected with *COROT*, we have estimated the number of events that should be detected during a two and half years mission. Two cases were contemplated : multi-transit (N > 2) and transits identified by their characteristic colours. For a given couple of stellar apparent magnitude and orbital distance of the planet, one can determine the minimum S/N ratio (and thus size of the planet) allowing the detection with one or the other method. Taking then into account the geometrical and temporal probabilities to have – for this orbit – one transit during the observing period, as well as the density of stars of this magnitude and spectral type in the line of sight, the number of expected detections is derived. Since there is no model of the orbits distribution in an average planetary system, we have chosen a presentation of the results that allows each one to derive the information he prefers. We plot the curves of iso-number of detections – on one field – in the plane of reduced orbit vs planetary radius. The plot is then read as follows : if all stars would have a planet of radius R at reduced orbital distance a, then the number of detection would be given by the label of the contour crossing the point (R, a). Fig. 5 summarizes the result of the prediction model in the case where the fields are at $b_{II} = 10$ deg.

Jupiter-type planets. Assuming that *COROT* will survey fields at $b_{II} = 10^o$ and $R_{pl} = R_{Jup}$, we derive from Fig. 5 that *COROT* should detect a large sample of this class of *hot Jupiters* popularized by RV measurements. If we take as a basis T_{pl} =1300 K and assume 2 % of stars with a Hot Jupiter, a fraction derived from RV data , then all of those planets with orbit properly aligned should be detected, i.e. about one hundred. Note that the chromatic information will also bring in a fair statistics on big planets in the 0.7 - 1.6 AU range (*warm Jupiters*). For instance, if Jupiters with a close to 1 AU are not rare, then a fair number of them should also be detected ($\approx$ 100 at maximum if they are very frequent).

Earth-Uranus planets. The fraction of stars with Earth-like planets is obviously very uncertain. If we assume however that rocky planets, i.e. with $R_{pl}/R_{\oplus} < 2.2$ (Wuchterl, Guillot and Lissauer, 1999), are frequent, then , with the same galactic model and in the basic mode of *COROT* (multi-transit), up to 50 planets could be detected if their orbital distance is between .3 to .5 AU. With the chromatic information, mono or dual transits of sufficient S/N are also usable and the number of detected planets could reach 15 in the 0.5 - 1 AU range of orbital distance, i.e. possibly in the habitable zone (we assume the average model of Chyba, Whitmire and Reynolds, 1999). The number of detections of Uranus-like planets, i.e. with radius close to 4 $R_{\oplus}$ would be much larger, if such objects are indeed frequent : this number could be as high as 100 at 1 AU and 200 at 0.5 AU.

Of course the previous numbers are *maximum maximorum*, since they are based on the unrealistic ass-

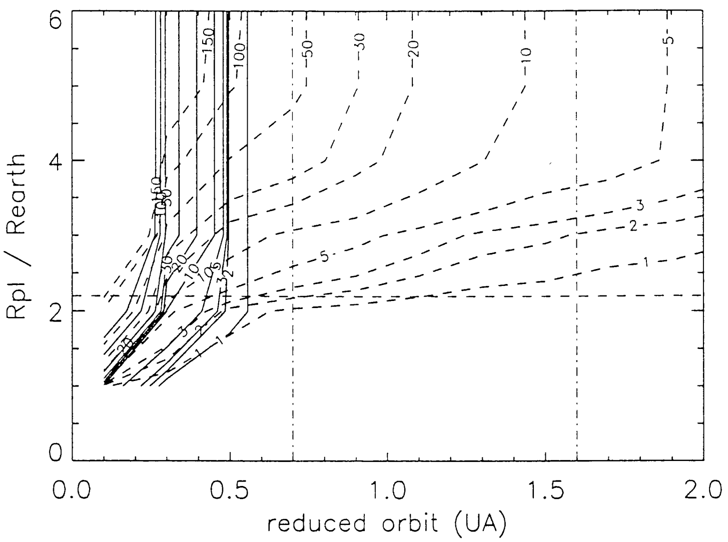

Figure 5. Plot of number of expected number of planets detected by *COROT* according to their radius and orbital distance to the planet. The labeled number on each curve corresponds to the expected number of detections on one field of *COROT*, assuming all stars with a one-planet system. Solid lines are detections based on multi-transit ($N > 2$) only, while dash lines correspond to a detection thanks to chromatic discrimination (see text). The field is supposed to be at $l_{II} = 30^o$ and $b_{II} = 10^o$.

sumption that all stars have a planet of the considered type, but even if only 5% of such systems do exist, the number of detections still remains significant and will allow us to answer some basic questions related to the optimization of the DARWIN mission.

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