COROT: ASTEROSEISMOLOGY AND PLANET FINDING

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Abstract

The COROT project, developed in the framework of the CNES small satellite programme with a wide european cooperation, will be launched in 2004. It is dedicated to seismology and detection of telluric planets.

It will perform relative broad band photometry in visible light, during very long (150 days) observing runs in the same direction. Both programmes are working simultaneously on the same region of the sky. The seismology programme aims at mapping the HR diagram and study in details approximately 50 targets brighter than 9th magnitude. Another 50 will also be observed with a lower accuracy. The exoplanet programme will search for telluric planets slightly larger than the Earth, in the habitable zone and closer.

Key words: Stars: structure – Planets: exoplanets – Space: photometry

1. Introduction

COROT, which stands for COnvection, ROtation and planetary Transits has been developed as a minisatellite, i.e. a mission of intermediate size and low cost. Its total mass is less than 600Kg. Its total cost remains below 80MEuros.

It was proposed already in 1993 by C. Catala, M. Auvergne and A. Baglin (Catala et al., 1994) in answer to a call for ideas of CNES for "small missions", using the generic CNES platform called PROTEUS and was preselected in 1994 for a launch three years later.

At that time it was designed as a second generation mission of asteroseismology only, following EVRIS (Baglin et al. 1992) and preceeding a large survey like STARS.

However, political and financial difficulties have postponed the final decision, which was taken only in October 2000. In between, the studies have continued, and we have been able to propose a much richer scientific mission, in particular in including a planet finder objective. The scientific community is also much larger as many european countries have joined the project.

Now, COROT has entered phase C/D and the launch is planned at the end of 2004.

CNES has the global responsibility of the mission. In France, three space laboratories (DESPA, IAS and LAM) contribute to the hardware, and many more to the scientific preparation.

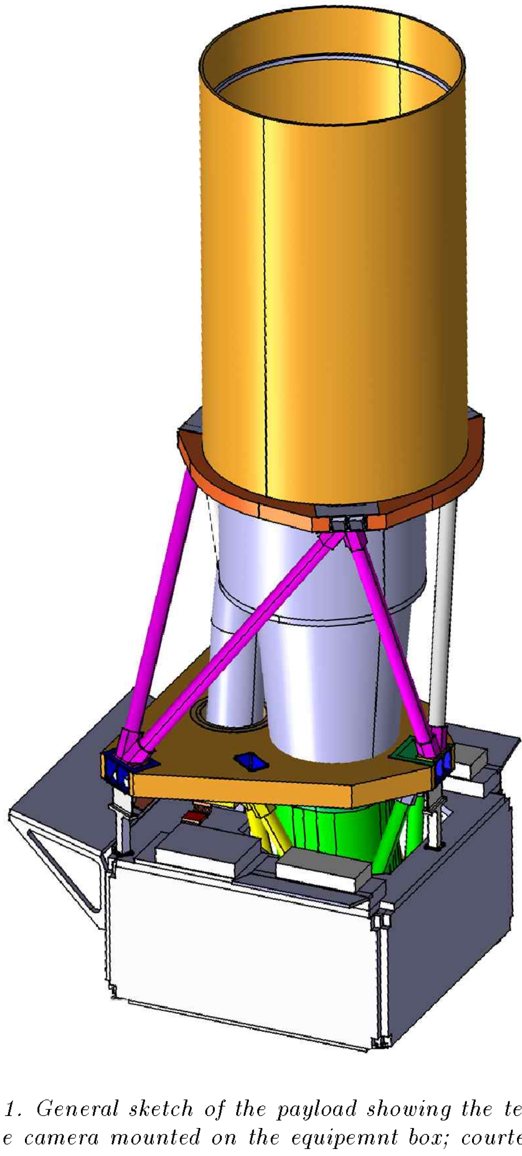

Figure 1. General sketch of the payload showing the telescope and the camera mounted on the equipemnt box; courtesy Ch. Imbert.

Contributions on the instrument and the ground segment come from RSSD/ESTEC, Austria, Belgium, Italy, Germany, Spain and the ESA Science Programme. Many observers from all over Europe contribute to the ground-based preparation.

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COROT, with its two programmes, is a pathfinder and is definitely a precursor of EDDINGTON. The knowledge on ultra-high precision photometry from space acquired in building COROT will certainly be very helpful in its definition and preparation.

More information can be found at: http://corot.astrsp-mrs.fr.

2. The Satellite and the mission

The satellite is 4.2 meters high, and is included in a cylinder of 1 square meter. It has two sets of 4 solar panels.

Two launchers have been preselected, Rockot from Eurokot and Soyouz from Starcem.

The instrument is a photometer, composed of an afocal telescope and a focal block containing 4 detectors.

The two scientific programmes work simultaneously on adjacent regions of the sky, use the same optics, and are separated only in the focal plane.

2.1. The mission profile and the observable sky

As COROT belongs to the PROTEUS programme, only low-Earth orbits are allowed. Long uninterrupted observations in the same direction of the sky are possible only with an inertial orbit, which is polar. The orbital plane can be chosen freely and will remain the same during all the mission.

The necessity to avoid the Earth limb to keep a very low level of straylight ($\sim$ a few electrons per pixel and per s.), limits the visible sky of Corot to two circles of approximately 10 to 15 degrees of radius, centered on the celestial equator. The position of these circles has been chosen to optimise the two scientific programmes: their centers are at a right ascension of 102.5 ($\pm$ 2) and 282.5 deg.

When the Sun reaches the orbital plane, the satellite is turned in the opposite direction to keep the Sun in its back (figure 2). Each half year period contains a long run (150 days) and 2 shorter runs (10 to 20 days).

The total duration of the mission is 3 years minimum, allowing for at least 5 long runs.

A very large duty cycle is required: 90% over 5 days , and 80% on 150 days, to avoid aliases due to gaps in the data.

2.2. The telescope

The telescope is an off-axis one, with an entrance pupil of 600 cm^2; this optical scheme has been chosen to reduce the internal straylight (figure 4). A very efficient baffling outside but also inside the telescope (attenuation of $\sim 10^{-13}$) protects from the straylight from the Earth.

The camera (figure 5) is composed of the dioptric objective which focusses the sky image on the detectors, and of the focal block which contains the detectors and a small bi-prism for the exoplanet programme.

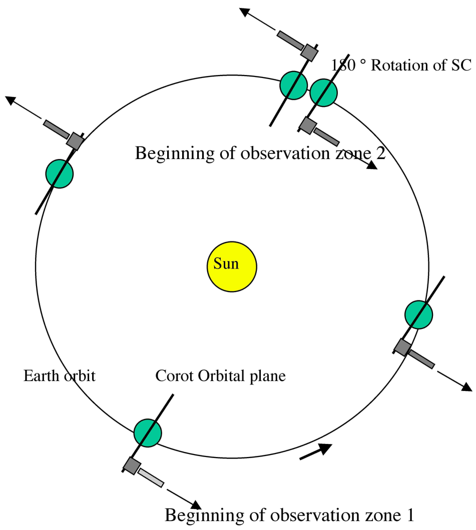

Figure 2. The satellite orientations during one year, showing the changes of pointing direction every six months; courtesy Frederic Bonneau and Laurent Boisnard

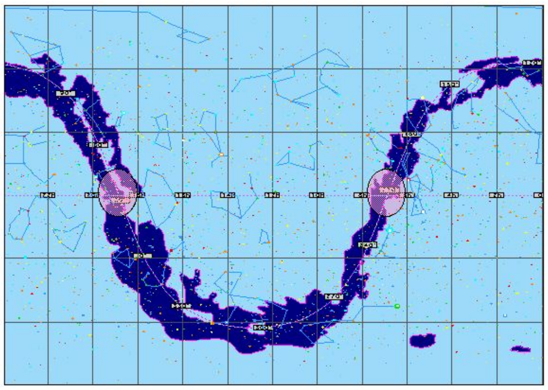

Figure 3. Observable regions of the sky centered on the celestial equator, at 102,5 and 282.5 deg *close to the galactic plane.*

2.3. The focal plane

The focal plane is composed of 4 2048x2048 Marconi MPP CCDs, working in frame transfer, at $-40\deg C$.

Two are dedicated to seismology and are highly defocused, to avoid saturation on bright sources.

Two are dedicated to the exoplanet programme and work in focus but with a small dispersion ($R \sim 4$), parallel to the rows of the CCD (figure 6).

The stability of the photometric information in the seismology field, specially respect to depointing, imposes

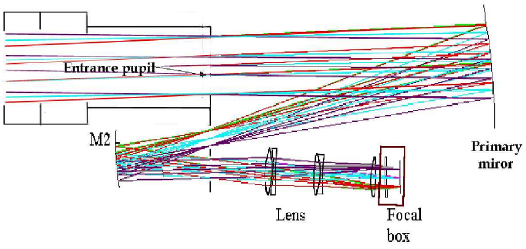

Figure 4. The optical scheme of the afocal telescope (primary and secondary mirrors), followed by the dioptric objective.

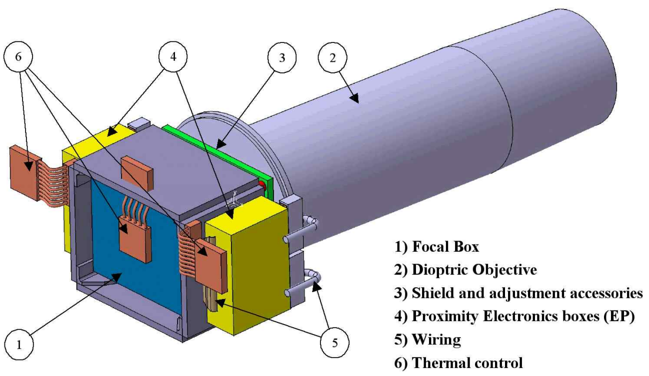

Figure 5. Sketch of the COROT camera, composed of the dioptric objective and the focal block containing the detectors; courtesy Ch. Imbert.

strong constraints on the defocused PSF, which has to remain regular, with no spikes, as shown on figure 7.

The best possible coloured PSF in the exoplanet field has a strong peak in the red and is more dispersed in the blue.

2.4. The CCD test bench

Meudon Observatory has developed and built a CCD test bench dedicated to high precision relative photometry. Specific experiments coupling the CCD response relative to the optical PSF, temperature fluctuations, position of stars on the CCD and defocus variations...are underway. They will allow to evaluate and control the noise budget through parametric analysis.

The major goals of this bench are :

- Technological test on the chip.
- Measurement of characteristics as a function of irradiation.
- Readout electronic and timing optimization.
- CCD Electrical Model characterization.
- CCD Flight Model calibration.
- Validation of high precision photometry.

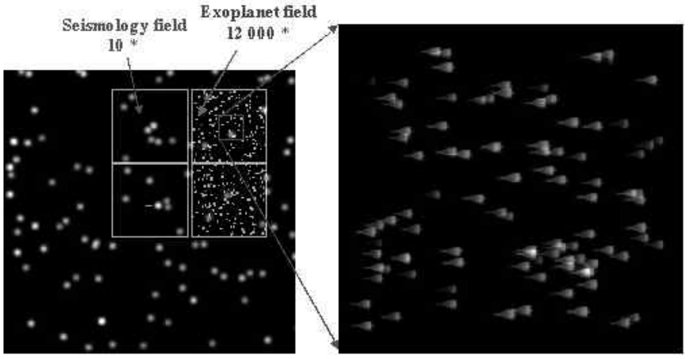

Figure 6. The sky around the primary target HD 43318 as seen on the detectors, showing the defocused seismology field with all the bright stars ($m_v \leq 9$) (left) , and on the right, an enlargement of the exoplanet field, with the dispersed images (right) ; the CCD size on the sky is 1.3 deg.

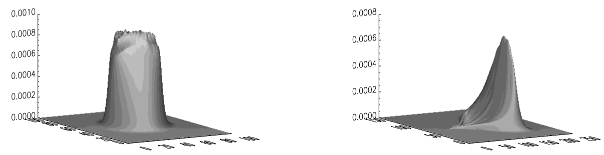

Figure 7. Spot image in the center of the seismology field (left), and of the exoplanet field (right)

This bench has a very high intrinsic stability, wide house-keeping monitoring and is flexible to allow easy modifications of the parameters.

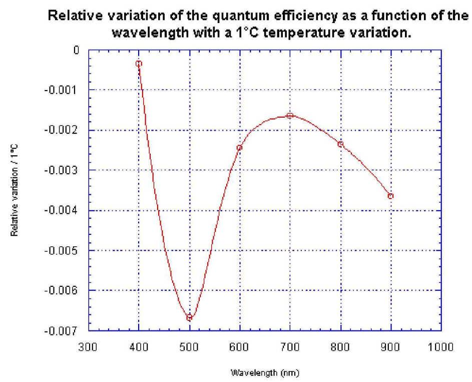

Figure 8. Relative variations of the quantum efficiency of the CCD chips as a function of wavelength, with a 2 degrees temperature variation

An example of recent measurements performed on this bench is given in figure 8, showing the chromatic behavior of the temperature dependance of the quantum efficiency.

3. The photometric performances

For the seismology field, it is required to detect a solar-like oscillation in a 6th magnitude star, in 5 days, which means a detection threshold of 0.66 ppm in 5 days.

In the exoplanet field a noise level of 7 10^{-4} in 1 hour is required on a 15th magnitude star.

These accuracies can be reached only after corrections of the major perturbators, as jitter, temperature variations, background....

A preliminary model of the instrument and of the possible instrumental corrections show that the scientific specifications are fulfilled.

The jitter is considerably reduced, down to 0.2", by replacing the ecartometry information from the star trackers of the PROTEUS platform by the same quantity coming from the scientific detectors, which is much more accurate. The background is measured on board. Many temperature sensors monitor the thermal behavior of the instrument, which is mainly modulated at the orbital frequency; on board as well as bench calibrations provide the necessary coefficients to perform ground based corrections.

The onboard treatment is kept as simple as possible, based on aperture photometry, and most of the corrections will be made on ground.

In the seismology field, the instrument will be photon noise limited (total noise/photon noise ≤ 1.1) down to the 9th magnitude (see Table 1).

In the exoplanet field, the photon noise remains the major source of noise down to 15.5 magnitude in white light and down to at least 14 in the blue part of the image.

4. The seismology programme

From the first days, the COROT seismology programme has been thought in the global framework of the ground-based and space efforts of the international community. It is highly motivated by the will to provide a very specific and unique insight on the seismic interpretation of "low" and moderate-mass stars on the main sequence. The mission profile has thus been deliberately organized around very long runs (150 days), for a limited number of targets (approximately 50). With these runs, COROT will provide seismic data with a precision and over time scales which are out of reach from the ground and out of the scope of any other so far planned space mission.

The general problem addressed by the COROT seismology Core programme is the nature of transport processes in stellar interiors during the Main Sequence evolution stage and around it. This covers several aspects of transport, from convective heat transport to angular momentum transport, including overshooting, transport of chemical species... Through these phenomena, we aim at deciphering the main sources of uncertainty in the modelling of intermediate and moderate mass stars during a stage of evolution which represents about 90% of their lifetime and has crucial consequences on their further evolution.

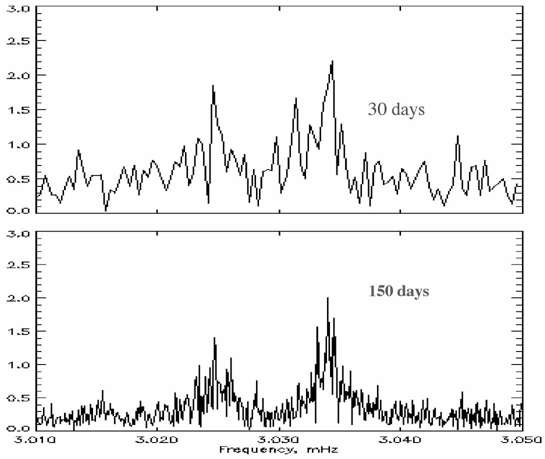

Figure 9. The 150 days and 30 days frequency resolutions, as illustrated by power spectra of IPHIR data over the same periods (Toutain and Fröhlich, 1992).

In the case of solar-like pulsators, it is well-known that the characteristic features of the internal structure (base of the convective zone, Γ_1 bump....) induce signatures in the oscillation frequencies at the level of $0.1\mu Hz$ (see e.g. Gough 91 and Provost 2000). Michel et al. (1995) show that with such a precision, we could pretend to disantangle the effects of the differents input parameters used in current stellar modelling. For moderate-mass stars like δ Scuti stars, Goupil et al. (1996) demonstrated that a 150 days run will provide accurate enough frequencies to tackle precise inversion of the rotational profile and thus address the key-aspect of angular momentum transfer in main sequence A-type stars (figure 10).

In the case of δ Scuti stars, the variation of the oscillatory behavior with time is still an open question. Such runs will allow time-frequency analyses on time scales of 5 months in great complementarity to what can be achieved from the ground where it is possible to follow (although with a lower sensitivity) an object over time scales of a few weeks (say 1.5 month) or years.

For both sets of objects, these data will bring a unique opportunity to investigate the physics at work at the edge of the convective core, a crucial source of uncertainty on the estimation of stellar ages for moderate and massive stars.

Besides these long runs, the COROT seismology Core programme also includes a few runs of 10 to 20 days. These runs will bring the opportunity, in observing of the order of 50 more objects to scan the oscillatory behavior accross the HR diagramme.

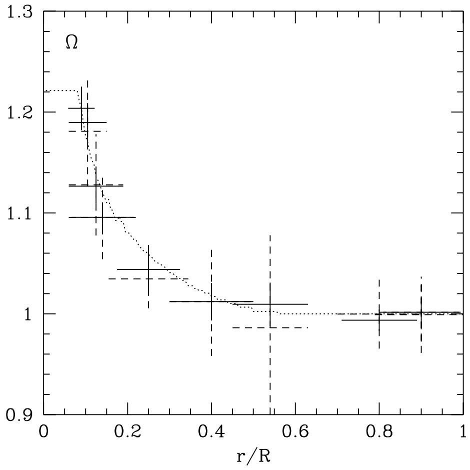

Figure 10. The role of the frequency resolution on the accuracy of inversion determination of the rotation profile of a late A star: the dotted curve represents the input rotational profile, the solid (resp. dashed) crosses indicate the results of the inversion and its accuracy assuming 150 (resp. 30) days of observation; courtesy M-J Goupil.

Table 1. Detection threshold σ and frequency resolution $\Delta\nu$ as a function of the V magnitude, for different lifetimes of the mode θ and for short and long runs, T.

V mag	T(days)	θ(days)	$\Delta\nu$	σ
6	20	5	0.6	0.65
6	150	5	0.08	0.65
9	20	5	0.6	2.5
14	20	20	0.6	13
14	150	150	0.08	4

5. The planet finding programme

Since the discovery of the first extra-solar planet (Mayor & Queloz, 1995), our ideas on planetary formation have changed a lot. Giant planets seems to form easily around their parent star, in contrast to the predictions of the "standard model" developped so far. Extra-solar planets have also unexpected orbital parameters (i.e) small semi-major axes or strong eccentricities, which brought the formation models into question. Does giant planets form following a core-instability mechanism or following a direct gravitational fragmentation? The old debate opens anew! Other mechanisms were also explored or revisited to explain the 51Peg-like planets as for example the migration mechanism due to disk tidal interactions. Migration was first investigated by Goldreich and Tremaine (1979) and is now considered to inevitably occur during the planet growth.

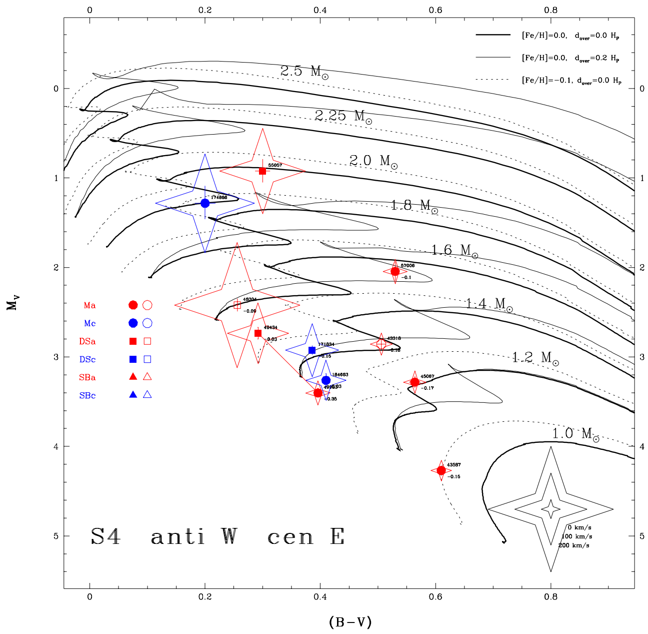

Figure 11. HR diagram of the principal target candidates of the seismology programme, superimposed on evolutionnary tracks of different masses and different population I chemical compositions; the size of the symbol incresases with rotational velocity; courtesy B. Popielsky.

After the discovery of the Giant exoplanet class, the challenge is now, to characterize the Terrestrial exoplanet class. It can be expected that further constraints will emerge from these new data and will help to significantly improve our understanding of the way planets form.

COROT is planned to take up the challenge with a planet finding programme whose main goal is to detect the first terrestrial extrasolar planets with the transit method. The problem is to detect the small luminosity decrease of a star when occulted by one of its planets, either a Giant with a Jupiter mass or a small terrestrial one. Of course this event may be observed only if the line of sight lies within the orbital plane of the planet. The associated geometrical probability is 0.5% for the Earth, 0.1% for Jupiter and 16% for 51 Peg b, so that a large number of stars must be monitored to have a chance to find a planet.

A transit event is characterised by:

(i) a relative amplitude of 10^{-2} for a Jupiter like planet and only 8.10^{-4} for an Earth like one;

(ii) a periodicity which ranges from a few days to several months.

The ability to detect a planetary transit also depends on the star characteristics (visual magnitude, spectral type, intrinsic variability) and on the performance of the instrument (aperture, focal distance, CCD, ..., see above). On the two CCDs devoted to the exoplanet program an amount of 6000 to 12000 stars, with magnitude mv = 12 to 16.5 and located at low galactic latitude, will be monitored continuously during 150 days, and this observation will be repeated at least 5 times. The integration time is 32 sec and the data is co-added on board every 17 min.

The expected performance in the detection of a transit on a mv = 13 quiet star at a 99% confidence level can be expressed in term of the radius of the smallest detectable planet; it is 2.3 $R_\oplus$ for a single transit event with a 10h duration and 0.9 $R_\oplus$ for a multi-transit event (40 transits) with a 3h duration. The detection efficiency has been estimated using improved methods of signal analysis on simulated light curves which account for the main characteristics of the telescope and under the assumption that the various noises are white and gaussian. Zodiacal light is the dominant source of white noise but is a stable one. Many tests were run with single and multiple transit events in front of a solar like star of a given visual magnitude. The results are presented in table 2 in term of the smallest detectable planetary radius and show that close-in planets similar to the Earth should be detectable with COROT.

Other detection tests were run also in the case of a star of a much stronger variability than that of the Sun. The light-curves simulated for that purpose are obtained through a simple scaling of a sequence of the VIRGO-SOHO data. The results are presented in table 3 when the variability scaling factor is of the order of 20 (see also figure 10 for other values of the scaling factor).

Over 150 days the longest observable transit period will be of the order of 50 days. A chromatic device has been added in order to partly overcome this limitation providing a multi-color information which helps to discriminate planetary transits from stellar artefacts. Indeed, transits are essentially achromatic events (geometrical effect) while stellar fluctuations are highly chromatic due to temperature variations on the star surface. A recent work (Defay, 2001) shows that, in the case of COROT, the use of a coloured information can improve the detection when the variability level of the star is much higher than that of the Sun (the variability scaling factor is larger than 20). Multi-color information is obtained thanks to a bi-prism located in the focal block at a few centimeters of the exoplanet CCDs.

The planet finding programme includes also deeper analyses of the future data and a programme of complementary observations in order to adress related scientific questions such as: (i) physics of the hot gas Giants thanks to radial velocity measurements; (ii) search for the signature of exoplanetary atmospheres and study of the star/planet interactions, thanks to high resolution spectroscopy; (iii) search for peculiar transits due planets in binary systems or to ringed (or mooned) planets.

6. The additional programmes

The idea of the Additional Programme section of COROT is to obtain a maximum scientific return of the mission. An Announcement of Opportunity (AO) will be issued to the scientific community at large about half a year before launch of COROT indicating two possibilities for a participation in the mission:

- Usage of the archival data. Successful proposals will have to address science outside the primary goals and will get access to specific archival data for proprietary use, but exclusively in the context of the science addressed in the proposal. Note that asteroseismology with the exoplanetary data and exoplanetary research with the seismology data will count as additional science.
- Propose short runs ($\sim$ 5) devoted to specific target fields.
- During the long runs, about 100 windows of the exoplanet fields will be available for additional science
- During the short runs of the core programme, it will also be possible to ask for specific windows in the exoplanet fields.

All response to this AO will be evaluated by the COROT Scientific Committee which will be in charge of the selection, taking into account the quality of the proposed science and the level of contribution by the participating countries and by ESA. A successful proposer will obtain status of a Guest Investigator (GI) and will have exclusive data rights for the science described in his proposal. The COROT Science Committee, however, will have the rights to use the same data for any other science.

One year after the first release of data to the Co-and/or Guest-Investigators the data will be released to the public.

In order to prepare the AO and to help defining the COROT Science an Additional Program Working Group (APWG) was established, presently consisting of the following subgroups:

- Planetary systems: comets, asteroïds, Kuiper Belt objects, etc.
- Pulsation: beyond the classical instability strip
- Stellar activity: a science case and a noise source
- Periodic stellar variability: rotation, binarity, etc.
- Links to space activities: ESO, NASA, CNES, etc.

Further subgroups can be formed on request.

Pilot studies will be developed by the subgroups in order to explore the parameter space available for additional science of COROT. Furthermore, a set of instrumental parameters has to be compiled and tested which will be needed for writing proposals as response to an AO. Such pilot studies (and future proposals) will have to address the following topics:

i) the scientific justification, background, objectives,
ii) the target list,
iii) why COROT should be involved,
iv) how COROT should do the observations (seismol-

Table 2. Radius of the smallest detectable planet (expressed in Earth radius $R_\oplus$) around a solar like quiet star. Transits (single or multiple) of a given duration, indicated between parenthesis, are detected around a parent star of a given magnitude using the matched filter and a periodic reference.

Magnitude	Single transit (10h)	6 transits (5h)	40 transits (3h)
12	2.0	1.4	0.8
13	2.3	1.7	0.9
14	2.7	2.1	1.4
15	3.5	2.8	2.0
16	4.7	3.5	3.0

Table 3. Radius of the smallest detectable planet (expressed in Earth radius) around a solar like star 20 time more active than the Sun (idem).

Magnitude	Single transit (10h)	6 transits (5h)	40 transits (3h)
12	5.1	2.5	1.8
13	6.0	2.7	2.2
14	6.9	3.2	2.6
15	7.5	3.7	3.0
16	8.3	4.4	3.9

ogy field, exoplanetary field, integration time, ...),
v) needed ground based support,
vi) simulation of COROT photometry,
vii) any additional information.

The APWG was also involved in the process of choosing the orbit parameters for COROT, and consequently defining the two continuous viewing zones centered at the celestial equator in opposite directions in the sky.

7. The ground-based observations

For an optimal selection of the observation programme for the seismology part of the mission, it is essential to gather as much a priori information as possible on all potential targets. In particular, a precise and reliable knowledge of their effective temperatures, surface gravities and detailed abundances is necessary. In addition, indications of their surface rotation rates, or their projected rotation velocities, is required to optimize the target selection. We also need to eliminate multiple stars in which the components have similar types, and finally we need to be aware of all peculiarities of each selected target (such as, e.g. high activity level). Finally, we need to check for the presence of polluting nearby sources, that might affect the photometric algorithms that will be run both onboard and on the ground.

While we already have some knowledge of the characteristics of the COROT potential main targets, we note that the potential secondary targets are not well-known, and in particular we lack knowledge of the luminosity class, metallicity, and rotation velocity of most of them. Besides, their spectral types, as taken from stellar catalogues, are sometimes not reliable, and their eventual multiplicity is often ignored. In addition, the knowledge of even the bright main targets is not sufficient to allow us to optimize their selection. In particular, the determinations of their effective temperatures, surface gravities, and metallicities are not precise enough, and most of them have no measurement of their surface rotation. In most cases, there is no detailed abundance analysis available.

This is why an ambitious ground-based programme was launched to answer all of these questions, and gather all of the necessary information on the COROT potential targets. This programme has several components.

- *Stromgren photometry:* we perform Stomgren uvby-Hβ photometry of all COROT potential targets. We use the semi-automatic photometric 80cm telescope at Pico Veleta (Spain). These data are used to derive estimates of T_{eff}, log g, metallicities. These observations are about half complete.
- *High resolution echelle spectroscopy:* these additional observations are necessary to obtain an independent and precise measurement of T_{eff}, log g, of the detailed element abundances, and of the projected rotation velocity. Besides, echelle spectra can allow us to detect multiple systems, as well as any spectroscopic peculiarity that could have an impact on the target selection. These spectroscopic observations are being conducted on 2m-class telescopes equipped with high resolution echelle spectrographs (R=30,000- 40,000) : OHP 1.93m/Elodie, SAAO 1.9m/Giraffe, ESO 152cm/FEROS. This part of the programme is also about half-completed today.
- *High angular resolution imaging:* these observations are important to know where polluting nearby sources are located to include this information in the photometric algorithms, and eventually to exclude stars from the target list in the most difficult cases. We plan to search for polluting sources within a few arcmin around

each selected star, using digitized Schmidt plates, then to perform adaptive optics imaging observations with the adaptive optics equipments of the 4m class CFH and TNG telescopes, in the immediate vicinity of the stars (up to 1 arcmin).

– *Ca II H &K index monitoring:* this type of observations is necessary to characterize the level of activity of the targets, and to determine their surface rotation period by detecting the rotational modulation of the Ca II H &K index. Although this will be possible only for the most active stars in the target list, we believe that the knowledge of the activity level and the surface rotation period is sufficiently important to justify this effort.

Most of these ground-based observations will be complete by the end of 2002, which will allow us to include the gathered information into the target field selection procedure.

In parallel to this ground-based preparation of the COROT seismology programme, similar efforts are being spent on the preparation of the exoplanet programme. The goal of these observations is to characterize the stars down to at least $m_V = 16.5$, in the fields potentially accessible to COROT. Knowledge of stellar temperatures and luminosity classes of stars is indeed necessary, first to identify the best candidate stars for exoplanet detection (i.e. cool dwarfs) in view of optimizing the selection of the monitored targets within the field of view, second to provide input for the selection of numerical masks for the onboard photometric extraction algorithm.

First estimates of the stars fundamental parameters will be obtained by using existing infrared all-sky surveys, such as DENIS and 2MASS, but better and more reliable determinations of the stellar temperatures and gravities will necessitate devoted observations. These observations involve broad-band and Stromgren photometry of several million stars, which will be obtained by using wide-field CCD imaging facilities at several places in the world.

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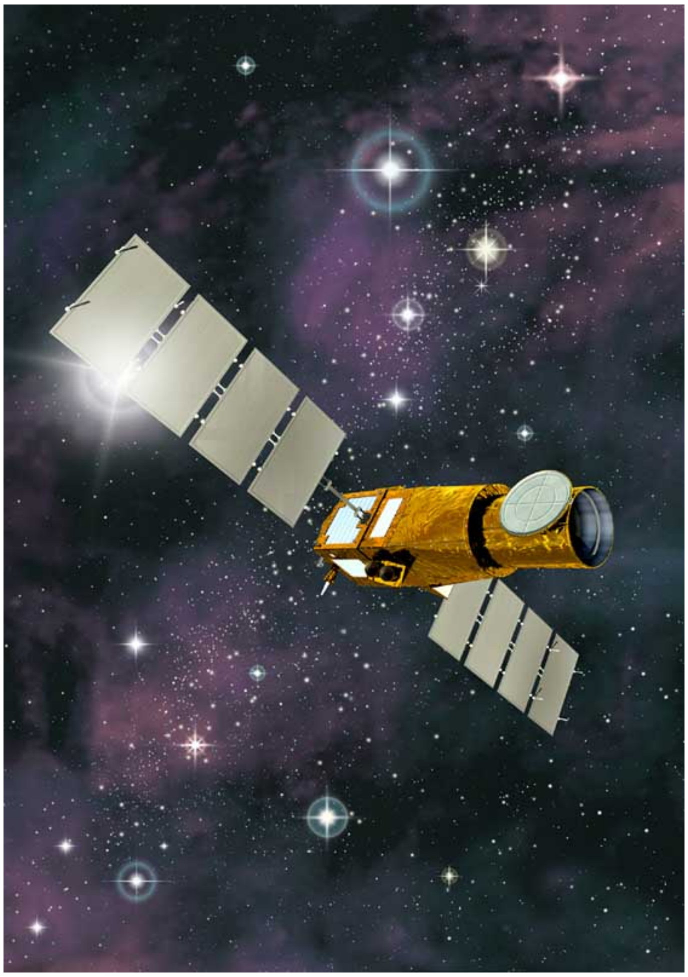

Figure 12. The COROT satellite in orbit around the Earth.