ASTEROSEISMOLOGY WITH THE SPACE MISSION COROT

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1. Introduction

Seismology from the ground has already provided many important results, as discussed for instance in Frandsen (1997) and in this symposium. The limitations of this approach are essentially the day-night alternance and the meteorological instabilities for photometry, the lack of photons and the broadening of spectral lines due to rotation for spectroscopy. Seismology from space is less limited, as photometry at a very high accuracy on long uninterrupted observing runs is possible.

Several projects, i.e. (Hudson *et al.*, 1986), (Praderie *et al.*, 1988), (Badialdi *et al.* , 1996), (Baglin and Auvergne, 1997), have been proposed since the first workshop dedicated to the subject (Mangeney and Praderie, 1984). EVRIS was the first one to be selected (Baglin, 1993), but unfortunately it has been lost in the crash of the MARS 96 spacecraft.

For the moment the only project which is decided and funded is COROT (for Convection and ROTation), in the framework of the "Petites Missions" program of CNES, the French Space Agency. The launch is scheduled in 2002. Several European countries contribute: Spain, Austria and SSD/ESTEC/ESA.

COROT has two independent scientific objectives, both requiring very long uninterrupted observations of the same stars with a very high photometric accuracy. Stellar seismology is the original and primary objective, and defines the characteristics of the instrument. The secondary objective is the search for transits of extraterrestrial planets over the disk of their parent star.

2. Basic scientific specifications for a photometer dedicated to asteroseismology in space

The basic principle relies on the ability to detect a periodic oscillation in a noisy signal and to measure its principal parameters (frequency, amplitude, lifetime) with a certain accuracy.

F.-L. Deubner et al. (eds.), New Eyes to See Inside the Sun and Stars, 301–308.

2.1. DETECTION THRESHOLD

The photometer "counts" events (in fact electrons) directly related to the photon flux emitted by the object, polluted by the different sources of noise, including the unavoidable photon statistics.

To make things simple, let us assume that the noise is white, with a variance σ. The periodic signal has an amplitude a, a life-time τ and is observed during a period T; the mean value of the number of counts per second is N_e. Defining $t = inf(T, \tau)$, the signal to noise ratio $\frac{S}{N}$, in the power spectrum is expressed as

$$\frac{S}{N} = \frac{N_e^2 t a^2}{4\sigma^2} \tag{1}$$

The challenge is to maximize $\frac{S}{N}$, which in any case is limited by the unavoidable photon noise. So, it is specified that the instrument be photon noise limited, in a given frequency interval, expressed as $\sigma^2 \leq \alpha\sigma_p^2$, where α is larger than, but very close to 1; $\alpha \sim 1.1$ is considered as the best realistic limit. The variance of the photon noise is $\sigma_p^2 = N_e$.

We also know very little about τ. For stochastically excited oscillations, τ is known only for the Sun, but should remain of the order of several days. The duration of the observations will always be longer than that, so that $t = \tau$, i.e. t is determined only by the star's behavior.

Then, in any seismologic photometer,we are left with the relation:

$$\frac{S}{N} = \frac{N_e \tau a^2}{4\alpha} \tag{2}$$

which relates a and N_e, at a given $\frac{S}{N}$, where

$$N_e = sd \int F(\lambda)\eta(\lambda)q(\lambda)\frac{d\lambda}{hc}\,, \tag{3}$$

s is the surface of the photon collector in cm^2;
d is the duty cycle, supposed to be constant in time;
$F(\lambda)$ is the photon flux received at the earth, outside the atmosphere, from a star of apparent bolometric magnitude m_b, as a function of the wavelength λ. It scales as $10^{-0.4(m_b-6)}$ and depends on the atmospheric parameters of the target, essentially its effective temperature;
$\eta(\lambda)$ is the transmission factor of the optical system;
$q(\lambda)$ is the total efficiency of the detector as a function of wavelength.
η and q have to be optimised, but do not vary much ($\eta q \sim 0.45$).

Thus, the minimum detectable amplitude a of an oscillation is related to its life-time, to the size of the collector and the magnitude of the target, through the relation

$$(\frac{a}{7\,10^{-7}})^2 = C\,(\frac{5}{\tau})\,(\frac{0.9}{d})\,(\frac{572}{s})\;10^{0.4(m_b-6)}\,, \tag{4}$$

.

where τ is expressed in days, and s in cm^2; $\eta q = 0.45$, and C is a constant slowly varying with the effective temperature of the target (C=1 for $T_{eff} = 6000\ K$).

For a detection at a confidence level of 99% in a white noise, one needs $\frac{S}{N} \sim 4$. As was shown e.g. in Baglin (1989), it is already possible to reach the level of the solar oscillations on a few very bright stars with an entrance pupil smaller than 10 cm diameter. If the size of the telescope increases, the number of objects accessible at the same confidence level increases, and for the same objects the detection threshold is lowered and the confidence level of a given mode is increased. The solar oscillations ($a \sim 2.5\ ppm$) will be detected with a 27 cm collector at a confidence level of 99% for a 6th magnitude star. We will see later that this is the goal of COROT.

2.2. FREQUENCY MEASUREMENTS

In Fourier space, the frequency resolution $\delta\nu$ is the inverse of the total duration of the observation T. However, the accuracy of the measurement of the frequency of a mode depends on the time properties of its excitation, as shown by Libbrecht (1992), and this accuracy approaches $\delta\nu$ only if the signal to noise ratio is large. The need for precise frequency determinations to interpret the data requires long duration observations and high signal to noise ratios. Approximately 150 days and $\frac{S}{N} \sim 4$ are needed to reach an accuracy of $0.1\mu Hz$.

As the detection threshold is approached with an observing run covering the lifetime of the mode, increasing the length of the run improves essentially the accuracy of the frequency determination. If, as seen in the Sun, a given mode is not always present, it will also increase the probability to detect more modes.

3. The COROT program of asteroseismology

3.1. EXPLORATORY PROGRAM

As COROT is the first mission dedicated to asteroseismology, a preliminary program called "exploratory" will determine the domain of stellar parameters for which oscillations are detectable, and the relation between the amplitudes of the solar-like oscillators and their characteristics. Though several theoretical predictions of the amplitudes of oscillations excited stochastically by convective motions exist (Houdek, 1994; Goldreich et al., 1994), a large uncertainty remains, in particular on the treatment of the superadiabatic external layers and on the scaling of the turbulent velocity field.

To do so one has to observe a sample of objects with a variety of stellar parameters, i.e. mass, age, chemical composition, state of rotation...but with moderate signal to noise ratio and frequency resolution: $\delta\nu \sim 0.5\mu$Hz is sufficient for that purpose, corresponding to observing runs of 10 to 20 days. Stars down to the 9th magnitude are appropriate targets (see Section 4.4), and 5 to 10 will be observable at the same time (see Section 4.5).

Several tens of stars will have to be followed, corresponding at least to 2 to 4 months of observation.

3.2. CENTRAL PROGRAM

More ambitious and more time consuming than the exploratory one, the central program corresponds to the second step in the development of space asteroseimology. It aims at observing very precisely a small set of objects, selected for their diagnostic power. The choice of the targets will be determined by the results of the exploratory phase.

Based on the solar case, we fix the accuracy of the frequency measurement at $\delta\nu \sim 0.1\mu Hz$ to have access to mode profiles and rotational splitting and to measure precisely the distribution of the mode frequencies. For a 6th magnitude star (see $ 2.1), the detection threshold is below 1 ppm. For A and F stars close to the main sequence, it will then be possible to measure the size of the convective cores (Michel et al., 1994; Roxburgh et al., 1996), the size of the outer convective zones and their helium content (Gough and Kosovichev, 1993) or the rotation profile of δ Scuti stars (Goupil *et al.* , 1996).

A least 5 runs are planned, during which one bright star (the main target) and several fainter ones in the surrounding field of view will be followed.

3.3. STELLAR VARIABILITY SURVEY

The secondary objective of COROT is the search for extraterrestrial planets. To do so, COROT observes during the central program of seismology in a neighboring region of the sky. It will follow of the order of ten thousand objects simultaneously down to magnitude 16, with an exposure time of 15 minutes, producing light curves of more than 50 000 stars, with an accuracy of a few 10^{-4}. The continuous time coverage, as required for seismology, will give access to the precise time behavior from 1 hour to 100 days.

In addition to the search for transits of exoplanets, this wealth of information will be used to study variable phenomena, erratic or periodic, on these time scales. At this level of accuracy, rotation modulation, activity and spots will be detectable, and a statistical study of variability in the HR diagram will be possible. This serendipity program will complement the HIPPARCOS variability results, which had a poorer time coverage, a smaller photometric accuracy, and a limiting magnitude around 12, but a larger sample of objects (Eyer and Grenon, 1997) .

4. The instrument

The design of the instrument has to satisfy the four major constraints on the detection threshold, the noise level, the total duration of an observing run and the duty cycle. The constraints on the length of the observing runs and on the duty cycle depend essentially on the satellite and particularly on the orbit.

4.1. THE FRAMEWORK OF THE "PETITES MISSIONS" PROGRAM

The budget of a space program is a determining factor in defining a seismology mission, as it fixes the order of magnitude of the collector. The CNES "Petite Mission" program corresponds to a total cost of 200 MFF, but accepts some foreign complementary participation. It corresponds to a telescope of approximately 25 to 30 cm diameter. The PROTEUS platform, which has to be used for that mission can attain only low earth orbits. Fortunately, with a polar inertial orbit, observing runs up to 150 days are possible, on selected regions of the sky.

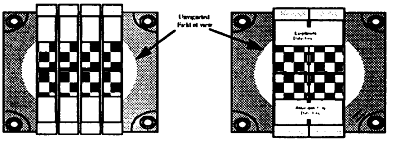

Figure 1. Two possible pavements of the focal plane with frame transfer CCDs; half of the chips are devoted to asteroseimology, the others to the exoplanet program.

4.2. SOURCES OF NOISE

As already mentionned, the condition is that globally, in the frequency domain of scientific interest, the photon noise dominates. This frequency domain, in which oscillations are preferably looked for, has been fixed in the range of $[\,0.1, 10\,]\ mHz$.

There are three main sources of external noise: the detection system, the pointing system and the environment. The major outside perturbators are the stray light from the earth, the high energy particles from the South Atlantic Anomaly and temperature variations forced by eclipses. They have two very different types of temporal behaviors: some are white (i.e. noise related to the detectors), but most of them are modulated at the orbital frequency (approximately $150\mu Hz$). As we are looking for frequencies, constraints are different when dealing with a white or periodic signal: white noise is directly comparable to the photon noise, and has to remain 10 times smaller. A periodic perturbation will create a signature in the frequency domain which could be taken as a stellar frequency. To avoid such a confusion the perturbation amplitude has to remain below the fixed detection threshold.

As the modulation at the orbital frequency is unavoidable, it is necessary to exclude a frequency interval around the orbital frequency from the scientific domain. In this interval, it will be almost impossible to extract valuable seismologic information, and efforts will be made to keep it as narrow as possible. A suitable correction procedure will help reducing the effect.

4.3. THE DETECTORS

The major constraints on the detectors are the need:

- for an imaging system with a wide field, to be able to observe a reasonnable fraction of the sky and many objects at the same time;
- to maximise the quantum efficiency;
- to reduce all intrinsic noises such as readout noise and dark current;
- to minimize the time between exposures and the readout time;
- to minimize the noise produced by unaccurate pointing;
- to minimize the sensitivity to cosmic rays.

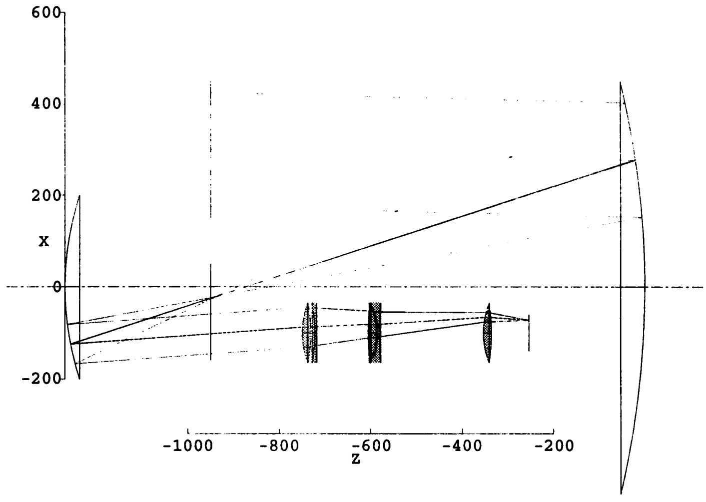

Figure 2. The optical scheme of the afocal telescope, with two parabolic mirrors and a dioptric objective.

These conditions lead us to choose frame transfer MPP (multi pinned phase) and back illuminated chips.

4.4. THE TELESCOPE

The design of the telescope is strongly constrained by the size of the entrance pupil (chosen here to be 27 cm) and by the need to minimize the amount of stray light from the earth entering the telescope. Varying periodically during the orbit, the flux of stray light at an altitude of $\sim$ $800\ km$ is of the order of $10^{17} photons\ cm^{-2}\ s^{-1}$. It has to be strongly reduced by a powerful baffling system. For that reason the preliminary concept (Baglin and Auvergne, 1997) of a classical off-axis, three mirror system has been changed. The best protection is reached with an off-axis afocal parabolic system (Figure 2).

The field of view will be of the order of 4 square degrees. It will contain a bright star (6th magnitude) and several fainter ones down to the 9th magnitude.

Pointing has to be treated with extreme care. The line of sight, during an observing run, has to be stabilised to better than 0.5 arcsecond, to keep the photometric fluctuations due to nonuniformity of the quantum efficiency of the detector below one tenth of the photon noise. This pointing stability will be mainly provided by the PROTEUS platform; if necessary, it will be complemented by an internal fine pointing system.

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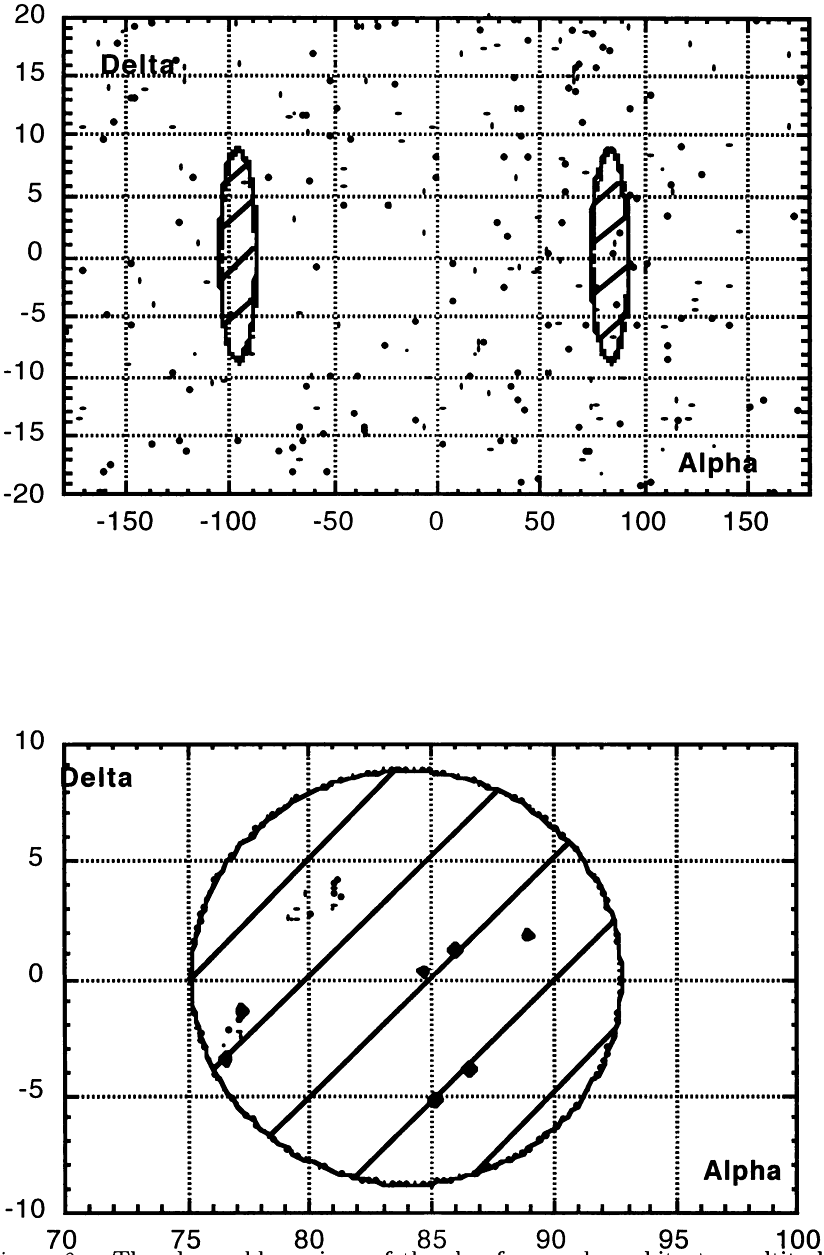

Figure 3. The observable regions of the sky, for a polar orbit at an altitude of 900 km, and a longitude of 0 degrees. On the upper panel, dots represent all the candidates for the main targets of the central program. The lower panel represents an enlargment of the observable zone. Dots indicate the best region for the central program, corresponding to a field containing a main target and several fainter stars of interest (see $ 3.2)

5. Mission profile

The only low earth orbits which allow the observation of the same star for several months are polar inertial orbits, the direction of observation being almost perpendicular to the orbital plane, i.e. close to the equatorial plane. To avoid eclipses and straylight from the earth, these directions are limited to small circles, as seen in Figure 3.

For a given position of the orbital plane, fixed by the date of the launch, two conjugated zones are acceptable, 180 degrees apart.

The proposed mission profile starts with 2 to 4 months devoted to the exploratory phase. Then the sequence of 5 to 6 successive long runs of 150 days start, centered on a bright seismology target, during which the exoplanet program also works. At the end of a sequence, the satellite will point in the opposite direction, to start a new long run on a target belonging to the conjugated zone.

The exoplanet program requires observations at intermediate galactic latitude (20 to 30 degrees) to optimise the target density on the sky.

Though all those requirements look quite restrictive, we have shown that they allow the achievement of both the exploratory and the central program.

Complementary ground based observations will help to select the final targets.

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