ASTEROSEISMOLOGY FROM SPACE.

COROT and other projects.

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Abstract. The scientific objectives and the observational strategy of asteroseismology from space are presented. The projects proposed in different contexts are briefly reviewed, with a particular emphasis on the COROT experiment, now accepted for a launch in 2001 in the framework of the french "Petites Missions" program.

1. Introduction: scientific objectives and strategy

Since the discovery of solar oscillations and its brilliant success, the generalization of seismology to many stars has become a challenge, motivated by its powerful capacity of diagnostic of the physical state of the stellar matter.

Seismology of stars aims at determining the internal structure from the properties of the eigenmodes (frequencies, amplitudes, phases, lifetimes) , as described by Dziembowski (this colloquium). To do so, many modes are needed, for each individual object.

If one wants to understand stellar evolution and apply the theory, for instance, to the chemical evolution of the Universe, one cannot be satisfied to rely only on a single object. A new physical process tested on the Sun, as for example microscopic diffusion, has to be validated on a variety of objects of different ages, chemical compositions, state of rotation ....

But, the seismic information can be interpreted unambiguously only if the global parameters (mass, chemical composition, surface temperature) are known accurately.

J. Provost and F.-X. Schmider (eds.), Sounding Solar and Stellar Interiors, 345-356.

From the observational point of view, the aim is then to define instruments and observing conditions allowing us to detect and measure the properties of as many modes as possible on a variety of "well known"stars.

To do so, one has to look for extremely small periodic changes (a few ppm) of an observable quantity, as for instance irradiance or radial velocity.

Indeed, the success of helioseismology, both from the ground and from space missions, encourages to pursue and apply the tool to other stars. But, there are major differences between helio and asteroseismology, theoretical as well as observational ones.

The Sun is a peculiar object in many respects. Its structure is sufficiently simple so the asymptotic approximation for high frequencies is valid. This means in particular that the frequency of a mode is related in a straightforward way to its quantum number. In addition, its rotation rate is slow, and the multiplets are equidistant. These two properties allow us to identify easily the mode corresponding to a given frequency. This situation is restricted to the old low mass stars. For more massive and younger objects, even close to the main sequence, the existence of a convective core and of a large angular momentum, produce a much more complex spectrum of eigenmodes. For evolved stars, the shell structure leads to a very dense and messy spectrum.

The Sun is also the only star for which the global parameters (mass, radius, age) are directly and accurately measured. For other ones, age determinations rely on model fitting and so depend on the stellar evolution theory and physical assumptions. Radius is almost never measured and, in the best cases, masses are deduced from the orbital motion in double stars. Effective temperature and chemical composition come from detailed analysis if the target is bright enough.

Determinations of these parameters, needed to deduce a first approximation model, are then less precise than for the Sun. But, as seismology is a very sensitive tool to probe the internal structure, the frequency spectrum varies rapidly with the global properties of the star, as pointed already first by Gough (1987). Discrepancies between an observed spectrum and a predicted one can come either from an incorrect physical description, or from an incorrect estimate of the global properties.

This is why the first approaches in asteroseismology should choose their targets among the best known and the simplest stars.

From the observational point of view, the difficulties are also important. First, photons are lacking. The unavoidable photon noise, which decreases when the star brightens, limits the amplitude of the variations which can be detected, and favors the brightest targets.

Stars are seen without spatial resolution, which means that only low order modes can be seen. Fortunately, they are among the most interesting ones for stellar evolution, as they penetrate far inside the stellar cores and give information on the nuclear burning regions. But, the total number of observable modes remains small and limits the accuracy of the determination of the structure at least in the envelopes.

Finally, due to the Earth motion around the Sun, most stars are visible only for a few months from the ground, but sometimes for longer periods from space depending on the orbit.

2. The need to go to space

This subject has been largely documented already (see Harvey 1985). Frandsen (1996, this colloquium) has described what has been done from the ground already and how the situation could be improved.

Let us recall that, to perform an asteroseismology program and to reach the real diagnostic power of the seismologic tool, we need to measure the variations with time of a quantity affected by the oscillations, with a high accuracy on both frequencies and amplitudes. This translates into the following conditions:

1. Amplitudes $\geq$ 1ppm or 10 cm/s, relying on the solar values and theoretical estimates (i.e. Houdek 1995)
2. Signal to noise ratio in the amplitude spectrum ≥ 4
3. Frequency range [0.05, 20] mHz
4. Frequency resolution [0.1, 0.5] μHz
5. Visual magnitude down to $m_v \geq 10$

The performances in terms of detection threshold of the different techniques available on the ground, as discussed by Frandsen (1996), are still far from fulfilling all these requirements, up to now.

From the ground, the photometric accuracy is limited at high frequencies by the scintillation, which can be reduced only by increasing rapidly the size of the telescope and observing from high altitude. But, these improvements are limited, as the scintillation noise decreases only as $D^{-2/3}$, where D is the diameter of the telescope. The excellent results of Gilliland et al. (1993) indicate that for 2 to 4 meters telescopes in high altitude sites, the scintillation level is of the order of 6 ppm for a signal to noise ratio equal to 1, which means that to satisfy both conditions 1 and 2 extremely large telescopes are needed around the world.

In spectroscopy (either Doppler or Equivalent Width techniques), almost not affected by the transparency variations of the Earth atmosphere, the present results are promising. But, the detection of oscillations remains limited to very bright objects. Another difficulty arises when spectral lines are broadened by rotation. Though this broadening gives the possibility to observe high degree sectorial modes, the capacity to extend these methods to non-slowly rotating stars is not yet documented.

Let us show now how it is possible to satisfy the whole set of specifications with a photometer in space.

The tranquillity of the space environment, and in particular the absence of atmosphere, allows us to reach the unavoidable photon noise limit at high frequencies (see Buey et al. 1997), even on bright sources, though it implies strong constraints on all the instrumental sources of noise.

In this condition, the signal to noise ratio (SNR) of a pure sine wave of frequency f and relative amplitude a in a white noise of variance σ is given by Scargle (1982):

$$SNR = \frac{N_0^2 a^2 t}{4\sigma^2} \tag{1}$$

N_0 is the mean counting rate, $t = \inf(T, \tau)$ where T is the total observation time and τ the oscillation damping time.

The SNR value is determined by the instrumental stability through the σ value, all the other terms being imposed by the properties of the stars. As long as the noise is white, it is independent of the frequency.

Then, the detection threshold of the coherent variations is only determined by the number of photons collected, i.e. the diameter D of the telescope, for a given magnitude. For a standard photometer, using high quantum efficiency detectors, a detection threshold of 0.6 ppm is reached in 5 days when roughly

$$log(D/25) \geq 0.2(m_v - 6) \tag{2}$$

which shows that a reasonable entrance pupil allows us to observe a large set of stars.

Another very important condition to obtain information that can be used for diagnostic, is the accuracy on the frequency measurement. Let us rely on the estimate by Libbrecht (1992) in the case of a damped oscillation, showing that a SNR of the order of 15 (in the power spectrum) and a duration of observation of the order of more than 100 days are needed to reach the $1\mu Hz$ accuracy on the frequencies (Fig 1.).

And this condition is supplemented by a secondary requirement. To reduce the amplitude of the sidelobes of the observing window and to prevent from misidentification of frequencies, the duty cycle should remain larger than 90%.

Obviously, this very long duration of observation and high duty cycle needed to obtain the frequency resolution cannot be achieved with ground based networks.

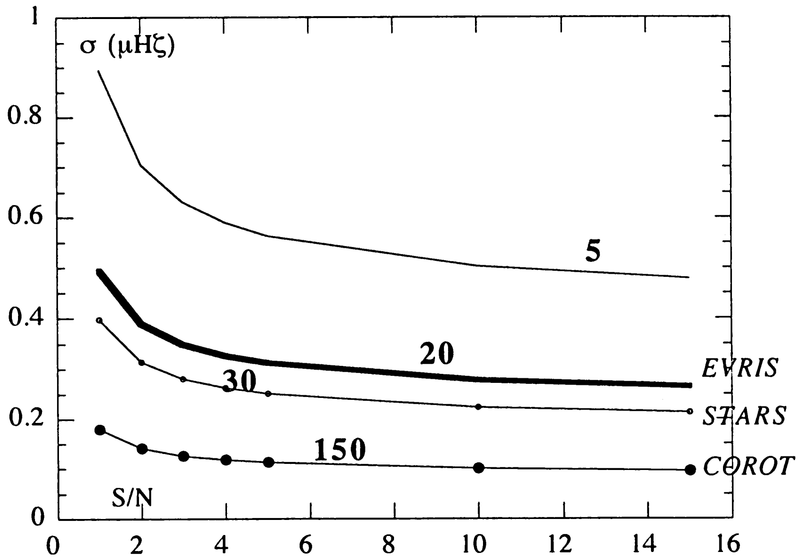


Figure 1. Accuracy on the frequency measurement from Libbrecht (1992), for the different projects.

3. The story of space projects.

The dream of asteroseismology in space has started in the early 80s with a proposal by the french group lead by F. Praderie and A. Mangeney (see Mangeney and Praderie 1984), followed by an Asteroseismology Explorer proposed by Hudson in the NASA context.

Different opportunities have been looked at since (see Noyes 1986), but none has gained a selection, except EVRIS, on board MARS96.

EVRIS, as a first attempt in the field, was designed as an exploratory mission, very small and cheap to be accommodated on an interplanetary spacecraft dedicated to the study of the MARS planet. It is described in Baglin et al.(1993), Buey et al. (1997) and Vuillemin et al. (1997). Its main scientific goal was to map the vicinity of the main sequence to determine the region where oscillations are sufficiently large. The main scientific return should concern the excitation and damping mechanisms, plus some insight in the internal structure, particularly for stars slightly more massive than the Sun (Michel et al. 1995)

Between the colloquium and the date of delivery of this manuscript, the MARS 96 mission has failed and EVRIS lies inside the ocean!

STARS, after PRISMA, has been submitted to ESA as a wide survey observing more than 100000 stars with a moderate frequency resolution, with particular attention to clusters (Badialdi et al. 1996).

COROT, presented in detail in the next section, has a different objec-

TABLE 1. Summary of the characteristics and status of the different projects.

characteristics	EVRIS	COROT	STARS	KEPLER
diameter(cm)	9	25	80	140
detector	PM	2 CCD in 2colors	4 CCD 1 color	$\sim$ 20 CCDs
FOV(degrees)		1.5	1.5	84
$< m_v >$	3.5	6	8-9	10-11
duration (days)	20	150	30 or more	4-8 year
lifetime (year)	0.7	2.5	2	4-8
nb. of targets	10-15	6+30	144 000	140 000
Trajectory	Earth-Mars	Quasi-polar	GTO	Heliocentric

tive. It aims at studying in detail a few well-known objects. Presently, it is the only one to be selected.

Let us mention that a new field of research is becoming interested in high precision relative photometry, i.e., the search for extrasolar planets through their transits across the stellar disk. The very similar instrumental constraints, as well as mission profiles (observing the same field for a long time) favors the idea of combining the two objectives. Several projects are being studied as for instance KEPLER submitted to the MIDEX NASA program, where the possibility of a seismological mode is under study.

4. COROT: stellar seismology, COnvection and ROTation

COROT was first proposed in 1994 in the framework of the french "Petites Missions" program (see Catala et al. 1995). Following EVRIS, it was dedicated to a detailed study of a few stars, specially chosen for their ability to provide precise tests on basic hydrodynamical processes, which are almost unknown in stellar interiors, focusing on convective regions (specially convective cores) and on the transfer and distribution of angular momentum.

After the EVRIS disaster, an updated version, including a program of detection of transit of extrasolar planets, has been selected by the CNES Science Program Committee on the beginning of December 96.

The present scientific program contains both the exploratory program, which should be realized by EVRIS, and the original COROT program.

4.1. SCIENTIFIC SPECIFICATIONS

They define the set of targets, the accuracy on the frequency measurement and the noise level. They are quite different for the two phases; constraints are softer for the exploratory program than for the main one.

4.1.1. *Exploratory program*

The targets are stars of spectral type B to G, of luminosity class V or IV. The objective is to detect their p-mode spectrum, and the splittings due to rotation. The corresponding scientific specifications are:

- Precision on measured frequencies better than $0.5\mu Hz$, which needs a duration of 20 days for one observation (Fig 1).
- Noise level less than 2 ppm over 5 days
- Duty cycle greater than 90 %

4.1.2. *Main program*

The best targets for this program are the F and early G main sequence stars, for several reasons.

The predicted amplitudes in late A and F stars close to the main sequence (Houdek et al. 1995) are larger than the solar ones, then easier to detect. These stars develop a convective core; its size, which is presently very badly known, provides information on the penetration of convective motions inside the stable layers; this process has important consequences on the evolution and in particular the ages. In addition, as these objects are still young, they rotate quite fast, and not yet rigidly; the rotational profile, derived from the splittings of the modes, will give tests of the processes of angular momentum transfer. Figure 2 shows how the rotation curve can be reconstructed from the measurement of the rotational splitting of the low order and low degree modes of a $1.8M_{\odot}$ star.

The late F and early G stars on the main sequence have extended outer convective zones. The concentration of Helium is unknown, as it cannot be derived from spectroscopy. Signature of the discontinuity at the bottom of the convective zone, and of the helium content are present in the behavior of successive frequency differences. Figure 3 shows how these frequency differences between two possible models can be measured, and interpreted to fix the most correct model which reproduces at best the observed spectrum. For instance, variations of 30% in the extension of the penetration region produce frequency differences of the order of 2μHz, easily detectable.

These two examples help to define the frequency resolution to be reached and the noise level. Then, the scientific specifications have been expressed as:

- Precision on measured frequencies better than $0.1\mu Hz$, obtained with a duration of 150 days for one observation.
- The noise level is fixed by imposing a SNR $\geq$ 4 and by the predicted amplitudes for the corresponding targets, i.e.
  * less than 0.6 ppm over 5 days for G stars
  * less than 2.5 ppm over 5 days for A and F stars.

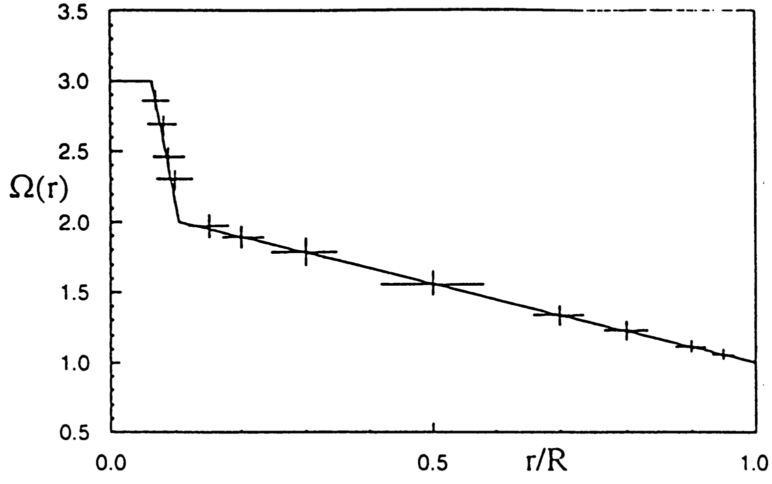


Figure 2. Determination of the rotational profile of a delta Scuti star, from Goupil et al. 1996. The full line represents the rotation curve introduced in the model to compute the splittings, whereas crosses indicate the results of the inversion of these data.

- Duty cycle greater than 90 % so that the side lobes of the window function remain negligible.
- Two colors photometry, to help the mode identification process.

4.1.3. *Secondary scientific objectives*

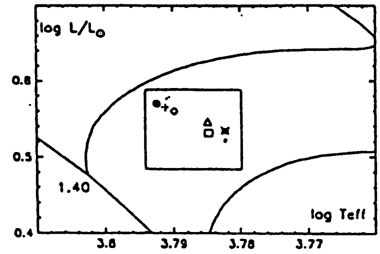
The observation of Jupiter in white solar reflected light is proposed as a secondary objective. The quantity which could be measured is the large separation ν_0.

As already mentioned, the mission profile of COROT allows us to propose a specific program of detection of Extra Solar Planets through the transits on the stellar disk. It will be realized by extending the field of view, to observe a neighboring region of the sky in a mode suited for this problem. This program is not described here.

4.2. DESCRIPTION OF THE EXPERIMENT.

4.2.1. *The spacecraft and the orbit.*

The "Petites Missions" Program provides the spacecraft called PROTEUS. It is an inertial platform, stabilized on three axes and designed for low orbit applications (maximum height at 1300 km). It includes a star tracker with a 20 degrees field of view, in charge of rough pointing. The mean power



model	$M/M_\odot$	Y	Z	d_{ov}	α
•	1.35	0.30	0.03	0.1	1.67
△	1.32	0.30	0.03	0.1	1.67
⋄	1.35	0.30	0.03	0.05	1.67
□	1.35	0.30	0.03	0.0	1.67
×	1.35	0.28	0.03	0.1	1.67
+	1.35	0.28	0.03	0.2	1.67
	1.30	0.30	0.03	0.2	1.67

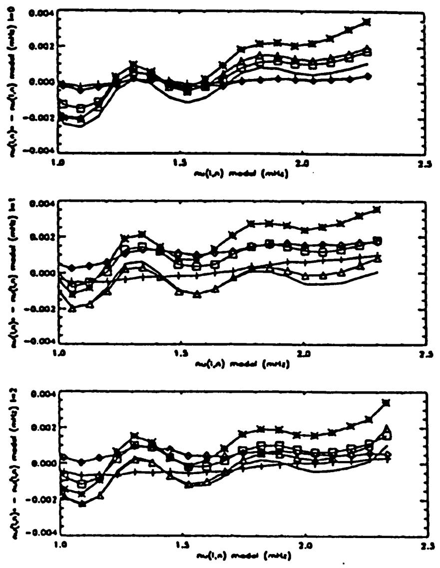


Figure 3. Frequency differences of low degree p-modes between a reference model, and different models compatible with the position in the HR diagram of the star β *Virginis*, from Michel et al. 1995

supply delivered to the payload is 150 W. and the total mass of the payload cannot exceeded 300 kg.

The spacecraft can be launched by a large variety of rockets.

To fulfill the specification on the duration of the observing runs, an inertial polar orbit at 800 km has been chosen; the visible regions of the sky are located along the equator.

The telemetry data rate is on average 600 Mbit/day to download scientific and housekeeping data.

4.2.2. *The payload architecture.*

The set of targets of the main program are the closest and brightest F stars compatible with the constraints on the orbit (see next section). This means that their average visual magnitude lies around 6. To reach the specified noise level, a pupil diameter of 25 cm is needed (eq. 2).

The telescope consists in an off-axis scheme with the advantages of no occultation and compactness. It is composed of three mirrors as shown on figure 4. Mirror M2 is used to stabilize the image in focal plane. As the orbit plane is not always perpendicular to the Sun-Earth axis the spacecraft flies over Earth regions enlighted by the Sun. A large baffle reduces the scattered light to a level smaller than 0.01 photons per pixel.

Two focal planes, one receiving the blue light and the other the red one, are composed of four buttable CCD each with 2000×4000 pixels of size $13-14\mu m$. Half of each CCD is used for frame transfer to avoid a mechanical

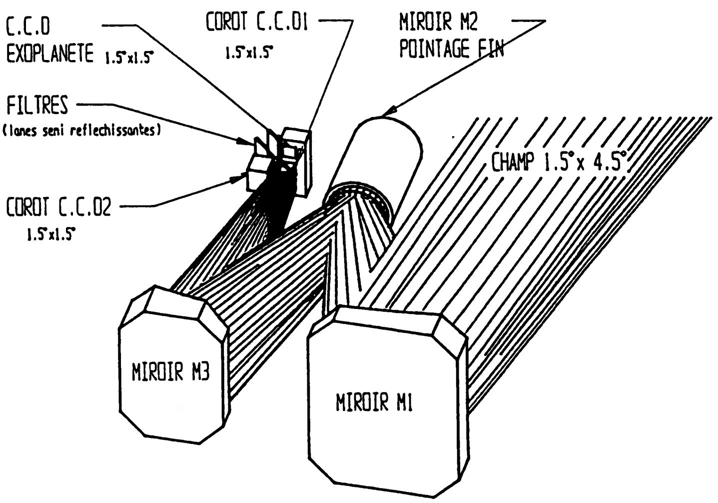


Figure 4. Scheme of the COROT telescope.

shutter. The CCD are thinned and backside illuminated. They operate in MPP mode and below – 50 C., to obtain a low radiations sensitivity. An aluminium shield of 12 mm. around the focal planes will cut all protons with energy less than 50 MeV and electrons with energy below 8 MeV. The readout noise will be less than $10e^-$ and dark current less than $2e^-$.

To avoid saturation on bright stars the focal plane is defocused giving a star image of 20 pixels diameter for the asteroseismology and 7 pixels for the exoplanets program.

4.2.3. *External perturbations.*

Most of the external perturbations are a consequence of the low polar orbit. They can be minimized and/or corrected. They are:

- Protons and electrons trapped in the SAA. They produce an aging of the CCD by increasing the dark current and reducing the charge transfer efficiency. The glitches in the image can be easily checked and corrected.
- Temperature variations due to the Sun occultations by the Earth. The quantum efficiency variation is typically 10^{-3} for one degree. Temperature variations will be known with a precision better than 0.01 K.
- Albedo variations during clouds and poles fly over. The Earth albedo can vary by a factor two around its mean value of 0.3. The scattered light induced variations will be checked on the CCDs.
- Coupling between the depointing and quantum efficiency variations from pixel to pixel. The angular stability of the image will be better

than 1 arc second.

4.3. MISSION PROFILE

In the first part of the mission, fields of view containing several stars of different types will be observed during approximately 20 days. Then, each field centered on a chosen target will be pointed during 150 days without interruptions. During this second phase, the exoplanet experiment will work permanently.

This long uninterrupted sequences can be achieved only for directions close to the equator and perpendicular to the orbit. But, it has been shown that a reasonable choice of adequate targets for the main as well as the exploratory programs satisfy these strong constraints. A launch in 2001 will permit also to reach Jupiter.

5. Conclusions

Several important results in stellar seismology can and will very probably be obtained from the ground, involving networks of moderate size telescopes. But, to achieve the overall scientific goals of this domain, photometry from space is certainly the best suited technique. With a quite small, simple and light photometer, one will have access to a wide variety of objects of different ages, chemical composition and internal structure.

Unfortunately, the difficulty to gain a selection among the different opportunities proposed by the space agencies, the failure of the MARS96 mission with EVRIS on board, and the unsuccessful STARS proposal in the "HORIZON 2000" context of ESA, have delayed the realization of such a program.

COROT is the next one to be launched in 2001, and let's hope that other more ambitious projects will appear.

There is certainly a strong need for an extended asteroseismology survey like STARS, even though no opportunity is presently foreseen.

Extremely high accurate photometry, as well as very long observing runs on the same field are also needed for programs of detection of transits of extrasolar planets, and combined missions are definitely an interesting challenge to look at.

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