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SIAMOIS: asteroseismology in Antarctica

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Abstract

SIAMOIS is a ground-based asteroseismology project, to pursue velocity measurements from the Dome C Concordia station in Antarctica. The scientific program of SIAMOIS is based on the very precise asteroseismic observation of nearby bright targets, focussing on the observations of solar-like oscillations in solar-like stars. Spectrometric observations with SIAMOIS will be able to detect l=3 oscillation modes that cannot be analyzed with space-borne photometric observations. The Doppler data, less affected by the stellar activity noise, will yield a more precise mode structure inversion, thus a high-precision determination of the stellar interior structure. The benefit of precise Doppler observations of nearby targets, with addition of interferometric and high-resolution spectrometric measurements, will allow us to investigate in detail the physical laws governing the stellar interior structure and evolution.

Dome C appears to be the ideal place for ground-based asteroseismic observations as it is capable of delivering a duty cycle as high as 90% during the three-month long polar night. This duty cycle, a crucial point for asteroseismology, is comparable to space-borne observations. The SIAMOIS concept is based on Fourier Transform interferometry, which leads to a small instrument designed and developed for the harsh conditions in Antarctica. The instrument will be fully automatic, with no moving parts, and it will require only a very simple initial set up in Antarctica.

Session: Future asteroseismic missions

Introduction

Stellar evolution theory is central to most areas of modern astrophysics. It plays for example a crucial role in the determination of distances and ages in the Universe. Stellar structure and evolution of stars was recently identified as a major domain of research for the next 20 years by the Panel "Evolution of Stars and Planets" of Astronet during the future prospectives workshop held in January 2007. The theory of stellar evolution, not sufficiently tested by observations, will benefit from the analysis of stellar oscillation modes: they propagate inside stars down to the core, and give a powerful tool to probe their internal structure. Thus, they provide the necessary observational basis for the theory.

Successful monosite asteroseismic observations have been performed recently with the échelle spectrometers developed for the search of exoplanets. Mostly sub-giants were observed. Individual eigenfrequencies were identified for the brightest targets; in other cases, only global oscillations parameters, such as the large separation, were measured. The window effect due to daily interruptions leads to large uncertainties and ambiguities in the frequency determination, and the frequency resolution remains limited by short observations. Two-site observations were performed on 4 bright targets (α Cen A and B, β Hyi, η Boo, see Bedding & Kjeldsen 2008), for about a week. The single network campaign for observing solar-like oscillation occurred in January 2007, on Procyon (F5, $m_{\rm V} = 0.4$): its central part, achieving a duty cycle of about 90%, was limited to 10 days (Arentoft et al. 2008).

SIAMOIS (in French for Sismomètre Interférentiel À Mesurer les Oscillations des Intérieurs Stellaires), to be installed at Dome C in Antarctica, will constitute a major step in the development of asteroseismology from the ground, using spectroscopy. Indeed, it will be the first asteroseismometer able to acquire the several months of continuous observations on the same objects that are required to obtain the frequency resolution necessary to carry out inversions of stellar internal structure. Duration and stability of the measurements will have the highest priority. The core of the scientific case will be completed with the observation of bright targets.

In this paper, we examine the reasons motivating ground-based Doppler asteroseismic observation, following space-borne photometric missions (CoRoT, Baglin et al. 2002; Kepler, Basri et al. 2005). We present the scientific program, with the great advantage of observing bright targets, for convergence of very-precise measurements obtained in interferometry, high-resolution spectrometry and asteroseismometry. The advantages of observing with a single site in Antarctica are then reported: the Concordia station at Dome C provides unique condition for a high duty cycle during 3 months. A few words on the SIAMOIS project are finally given.

Asteroseismic signal: Doppler versus intensity

Any project for the purpose of asteroseismology must answer the question: "What can this project achieve that has not been done by the CoRoT or Kepler missions?". The asteroseismic core program of CoRoT (respectively Kepler) consists in the observation of 6 main targets (about a few hundreds), for 5 months each (from 3 months up to 4 years for a few of them). CoRoT and Kepler are designed for faint targets, respectively about $m_{\rm V} \geq 6$ or 9, and will not observe the brightest stars.

Photometry and spectrometry observations are not sensitive to the same signal in the stellar photosphere. Photometry is sounding deeper regions, so that the photometric signal is corrupted by the different scales of granulation, whereas spectroscopic lines formed in higher regions are less affected by granulation. As a result, the low-frequency domain ($\leq$2 mHz) of the Fourier spectrum is much less contaminated by the activity and granulation signals at low frequency when observed in velocity. This was clearly demonstrated in helioseismology, and is also observed on stars (Fig. 1).

Therefore, spectrometric observations with SIAMOIS will be able to detect oscillation modes in the low-frequency domain, with much longer lifetimes. Longer mode lifetimes yield more accurate frequencies, then a more accurate structure inversion. In the solar case, inversion is 4 times more precise with Doppler data (Gabriel et al 1997). This is due to the fact that these data give access not only to the small frequency separation between $\ell = 0$ and 2, but also between $\ell = 1$ and 3. These small separations are crucial for asteroseismic inversion (Provost et al 2005). As a consequence, Doppler observations give a better asteroseismic signal, especially for low mass stars. However, only slow rotators ($v \sin i \leq 20$ km s^{-1}) present sufficiently thin lines for the benefit of spectrometric observations.

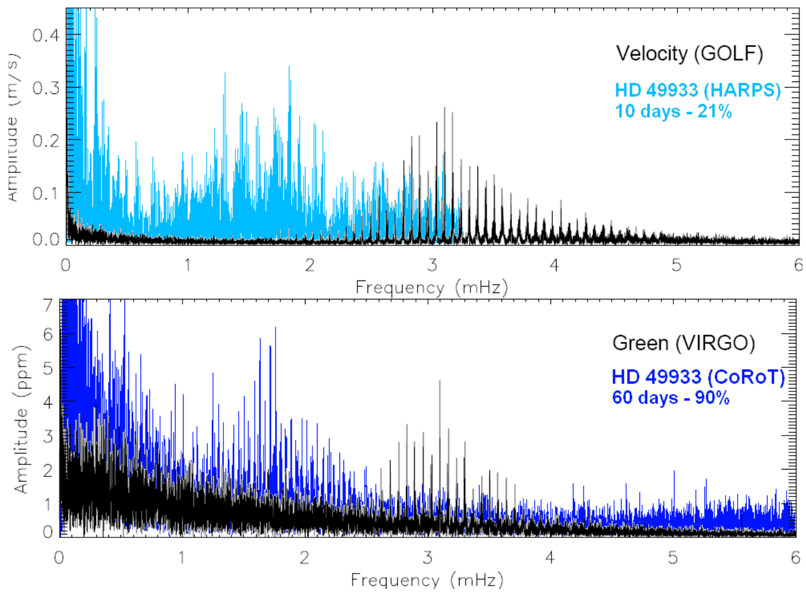

Figure 1: Comparison of spectrometric and photometric observations of the Sun (SOHO observations) and of HD 49933 (HARPS and CoRoT observations, Mosser et al 2005, Appourchaux et al 2008). For both targets, Doppler observations at 0.5 mHz remain photon noise limited, whereas the photometric signal include a significant contribution of stellar activity noise. The bushy aspect of the HD 49933 Doppler spectrum is due to a very low duty cycle (about 21 % of the single site observation of this CoRoT target)

Scientific case

The scientific program of SIAMOIS is based on the very precise asteroseismic observation of nearby bright targets, focussing on the observations of solar-like oscillations in solar-like stars. It includes also observations of classical pulsators (PMS, δ- Scuti), of solar-like oscillations in red giants, of gravity modes in γ Doradus targets. Possible circumpolar targets are represented in Fig. 2. Contrary to photometric observations, the list of targets includes a higher fraction of low-mass targets. Due to the instrumental requirement of observing thin lines, it concerns only slow rotators (Table 1).

This program is deliberately oriented towards bright targets. Contrary to the Kepler mission, which will focus on the statistical properties of a few hundreds of stars whose primary parameters are basically unknown, SIAMOIS will scrutinize in detail nearby stars. Thanks to astrometry, interferometry and high resolution spectroscopy, their distance, radius, $T_{\rm eff}$, $\log g$ can be very accurately measured. Creevey et al. (2007) have demonstrated the advantage to constrain the stellar modeling with asteroseismic data with an independent interferometric measure of the radius. Such bright targets can therefore benefit from convergent measurements, for a scientific program aiming to the determination of a sample of standards. As a result, the program will permit to address in detail not only the internal structure of the stars, but the physical laws governing their interior structure and evolution (see Table 2; a more detailed version of the scientific program of SIAMOIS is given at `http://siamois.obspm.fr/`).

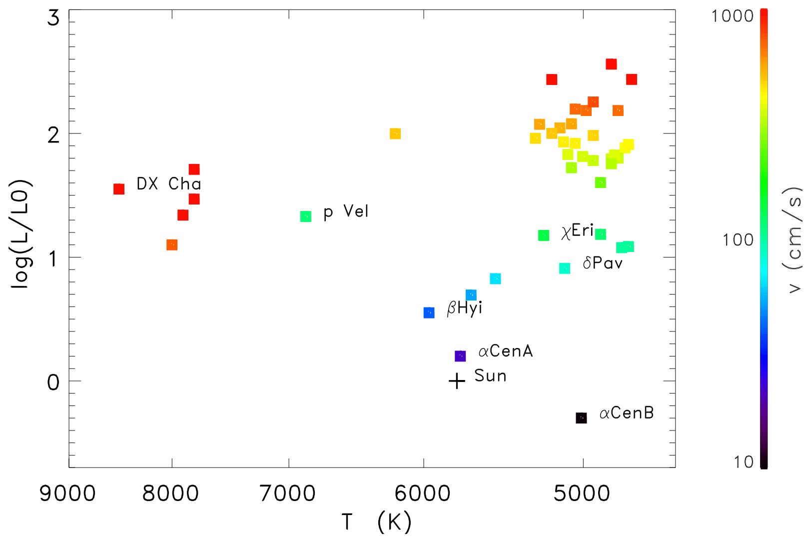

Figure 2: Identification of possible targets for SIAMOIS. All selected stars can be observed with a signal-to-noise ratio (in amplitude) greater to 6 after 5 days.

	space	ground
observation	photometry	spectrometry
max. degree	2	3
magnitude	dim	bright
$v \sin i$	–	$< 20\,\mathrm{km\,s^{-1}}$
inversion		4 times more precise

Table 1: Doppler versus intensity signal.

Observations at Dome C, Antarctica

Dome C is the only ground-based site allowing continuous observations for many weeks. On-site measurements during the 2005 and 2006 winterings show a duty cycle better than 90%, with long periods of time with full time coverage (Mosser & Aristidi 2007). On bright stars at high negative declination (α Cen, β Hyi), observations will be possible even at dawn and twilight. The seeing quality appears to be limited by the lowest atmospheric layers, yielding a moderate seeing at ice level, but excellent 30 m above the ground (Trinquet et al 2008). However, due to the large area (5") collected on the sky by its fiber, SIAMOIS will be rather insensitive to seeing, taking full advantage of the high duty cycle, independently on the photometric conditions. The high altitude of Dome C (3200 m, equivalent to 3700 m barometric altitude) will ensure high-quality performance. Dome C will also give access to continuous observations for as long as 3 months (duty cycle greater than 90% for more than 90 days, centered on the winter southern solstice), which is otherwise feasible only from space. April and August provide each a month-long period with a duty cycle about 60%, for specific programs withstanding a reduced duty cycle.

Network observations with non-dedicated sites present a duty cycle limited to less than 70% (e.g. WET network, Dolez et al 2006). With at least 6 selected observatories in excel-

- High-precision determination of the interior structure of nearby stars: primary parameters, age determination, composition
- Convection; diagnostic of convective cores; depth of convection and of second helium ionization zone; damping, excitation mechanism
- Non-linear physics, saturation effects, mode coupling; stochastically excited modes
- Comparative study: photometry / Doppler

Table 2: The scientific case of SIAMOIS

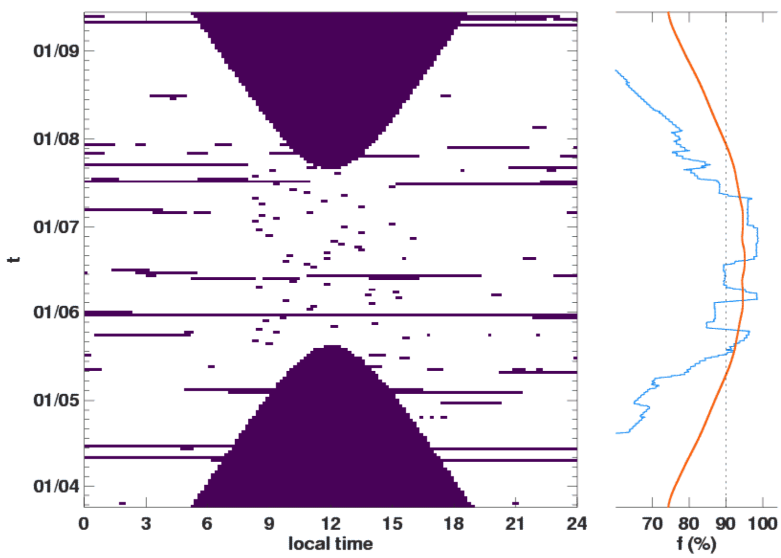

Figure 3: Left panel: simulation of the observation at Dome C, taking into account the Sun elevation, the bad meteorological conditions, and a daily 20-min interruption for operations such as telescope derotation. The Sun altitude limit has been fixed to $-4°$, for the observation of bright targets. Right panel: 10-day boxcar averaged duty cycle, and duty cycle integrated over the whole winter night.

lent sites, the performance of a network remains inferior to the Dome-C capability (Mosser & Aristidi 2007). It was stressed during the Astronet prospective workshop that both kinds of instrumentation are required for a better sky coverage. The Panel "Evolution of Stars and Planets" recommended a supporting facility instrument capable of performing long observations of high-precision stellar radial velocities for applying the tool of asteroseismology. Network observations as proposed by the SONG project (Grundahl et al 2007) are complementary to observations at Dome C. Like SIAMOIS, SONG proposes to use small collectors, and therefore its program is also focussed on bright stars, but with declinations near the equatorial plane. Due to the scientific specifications, both projects need an automatic and robust instrumentation, with the necessary incidence on both budgets. However, the SONG network intends to include 8 observing sites (8 domes and infrastructures, 8 telescopes, 8 instruments), when 1 site at Dome C is sufficient. Operations at Dome C will be of course demanding, but with better expected results (in SNR and duty cycle).

The ARENA network (`http://arena.unice.fr/`) has identified that the best niche for time series observation at Dome C is spectroscopy. In fact, even if photometric stability at

Target	Limit magnitude m_V	
	40-cm tel	2-m tel
solar-like oscillations		
- solar-like stars	5	8.5
- red giants	7	10.5
classical pulsators	7	10.5

Table 3: Limit magnitude for different types of targets, according to the diameter of the telescope.

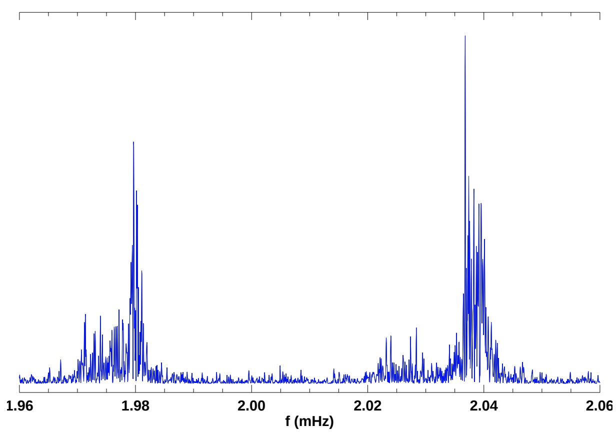

Figure 4: Photon-noise limited performance: 90-day observation, for a $mV = 4$ G0V target, and a 40-cm telescope (Mosser et al. 2003). The limited lifetime of the modes is responsible for the noisy aspect of the multiplets (from left to right: ℓ =2, 0, 3, 1).

Dome C is exceptional compared to other ground-based sites, duty cycle in spectroscopy will be better since spectroscopic measurements are much less sensitive to most of atmospheric noise, and can afford the presence of light clouds. Furthermore, the quality of ground-based photometric observations are surpassed by space-borne ones, whereas a Doppler instrument as SIAMOIS has no space competitor.

SIAMOIS

Échelle spectrometers such as HARPS at ESO used for single-site radial velocity measurements are complex and expensive instruments that are not suitable for Dome C, where only very limited technological support is currently available. Conversely, a Fourier Tachometer like SIAMOIS, with no moving parts, whose interferometer is designed to be installed without any fine tuning, and whose conception and design were directly dictated by the environment at Dome C is precisely what is required for observations in Antarctica.

The principle of a Fourier tachometer dedicated to asteroseismology is presented in Maillard (1996). The specifications of the project are derived from the analysis conducted in Mosser et al. (2003). The necessary stability of the instrument is provided by a monolithic interferometer with no moving part, which means that the optical setup at Dome C will be limited to basic image formation, without strong requirements. In the same way, the design is directly suited for quasi-automatic operations, allowing simple and reduced operations. The

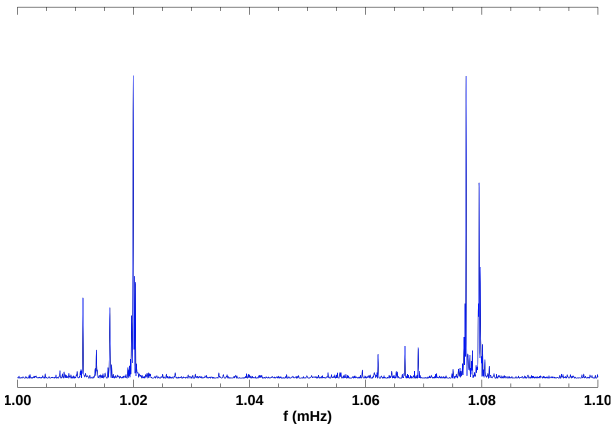

Figure 5: Same as Fig. 4, but with a zoom on a lower frequency range. Due to longer lifetimes, the modes multiplets appear very clearly.

fiber-fed instrument is operated at room temperature. A low-resolution ($\mathcal{R} \simeq 1000$) post-dispersion provides an efficiency greater by a factor of about 7 compared to a single bandpass. Photon noise limited performance insures a SNR better than 6, after 5 days observation, for all selected targets (and up to 30 for the brightest targets).

As continuous observation are mandatory for asteroseismology, the project includes a dedicated telescope. As the scientific goals are achieved with bright targets, a 40-cm class telescope is enough to provide "big science" at Dome C. First observations will run on bright targets such as α Cen A and B, β Hyi... with a a small dedicated telescope (Table 3). Other specific programs may require the use of a 2-m class telescope (such as PILOT, Storey et al 2007), as for example observations of solar-like oscillations in an exoplanet-host star (Vauclair et al 2008). In fact, with a 2-m class telescope, only oscillations in white dwarfs and subdwarf B stars remain out of the scope of SIAMOIS, because of their too faint magnitude.

Due to the multiplex avantage of a Fourier tachometer, the radial velocity information is coded with a very limited number of pixels. This makes possible to track on the same small CCD the signal coming from 2 fibres linked to 2 telescopes. Observing simultaneously with two dedicated small telescopes or with a 40-cm and a 2-m telescope will be possible, under the only conditions that exposure times are comparable. An automatic pipeline reduction will be developed, for real-time analysis in Europe, requiring a very limited band pass ($\simeq$ 100 kb/day for the scientific signal).

The phase A of SIAMOIS was completed in 2007. The design of the instrument takes into account the site, that is not a typical observatory offering many services for astronomy. The harsh observational conditions at Dome C impose stringent technological requirements, that translate in cost overruns: setup operation will be very limited; the instrument will operate quasi automatically. In fact, the phase A has shown that most of these requirements due to the site are similar to those of the project itself (sturdiness, high level of automation...); the cost to address the conditions in Antarctica is then limited.

A complete model of the instrument has been developed, and allows us to quantify the photon-noise limited performance. High SNR is reached for all targets presented in Fig. 2. Synthetic oscillation spectra are shown in Fig. 4 and 5. The noisy aspect of the multiplets in Fig. 4 is not due to a low SNR but to the limited lifetime of the modes in the high-frequency part of the pressure mode spectrum; fitting the Lorentzian profile of each component gives then the mode frequency, amplitude and linewidth. With a duty cycle as high as 90% during the 3-month long night, the precision on the eigenfrequency measurement will be as good as 0.2 μHz. Such simulations, compared to photometric results (Appourchaux et al 2008), shows the gain is signal-to-noise ratio when observing the Doppler signal.

Conclusion

After a score of 1-site Doppler asteroseismic observations of solar-like oscillations in solar like stars, a limited number of 2-site observation, up to date only 1 network Doppler observation, and before a possible network (Grundahl et al 2007), observing in Antarctica is required for long uninterrupted asteroseismic time series. As the observation conducted at the South Pole for helioseismology (Grec et al 1980), SIAMOIS will represent a major step in Doppler asteroseismology. With a small collector, SIAMOIS will achieve a consistent scientific program, to be conducted over more than 3 winters (ideally up to 6). According to its characteristics, SIAMOIS can be among the very first scientific projects to be conducted at Dome C.

The access to the low-frequency domain, to lower mass targets, to $\ell = 3$ modes makes Doppler observation at Dome C very competitive to space-borne observations, providing much more precise inversion results. When a photometric project as Kepler will yield a statistical approach on a large population of faint objects, SIAMOIS will look in great detail into nearby stars. Compared to the complementary space missions, SIAMOIS can really achieve "Big Science" at Dome C, even with a small 40-cm telescope.

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