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ASTEROSEISMOLOGY AT THE CONCORDIA STATION IN ANTARCTICA

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Abstract. SIAMOIS is a project devoted to ground-based asteroseismology, involving an instrument to be installed at the Dome C Concordia station in Antarctica. SIAMOIS provides an asteroseismic programme that can follow the way currently opened by the space project CoRoT, with unique information on G and K type bright stars on the main sequence. In addition, spectrometric observations with SIAMOIS will be able to detect oscillation modes that cannot be analyzed in photometry: the Doppler data, less affected by the stellar activity noise, yield a more precise mode structure inversion. The SIAMOIS concept is based on Fourier Transform interferometry. Such a principle leads to a small instrument designed and developed for the harsh conditions in Antarctic. The instrument will be fully automatic, with no moving parts, and a very simple initial set up in Antarctic. The dedicated scientific programme will avoid the complications related to a versatile instrument. Data reduction will be performed in real time, and the transfer of the asteroseismic data to Europe will require only a modest bandwidth. SIAMOIS will observe with a dedicated small 40-cm telescope. Dome C appears to be the ideal place for ground-based asteroseismic observations. The unequalled weather conditions yield a duty cycle as high as 90% over 3 months, as was observed during the 2005 wintering. This high duty cycle, a crucial point for asteroseismology, is comparable to the best space-based observations. Long time series (up to 3 months) will be possible, thanks to the long duration of the polar night. SIAMOIS can be seen as one of the very first observational projects in astronomy at Dome C. Its scientific programme will take full advantage of the unique quality of this site, and will constitute a necessary first step in preparation of future more ambitious programmes requiring more sophisticated instrumentation and larger collectors

1 Introduction

The analysis of stellar oscillation modes constitutes a powerful tool to probe their internal structure (Table 1). Already applied to the Sun with remarkable success, this technique is now opening up to stars, but asteroseismic observations have very stringent requirements in order to give precise constraints on stellar modeling: duty cycle greater than 80%, over long intervals of time typically several month (Table 2). Most of the first ground-based observations conducted with ground-based échelle spectrometers were single-site observations. Hence most of them were obtained with a good SNR but with an unsufficient duty cycle, and all of them were get over a short number of nights (typically 5 to 10 nights). This strongly limits the precision of the inversion process (Table 3).

First space-borne microvariability observations were provided by the Canadian microsatellite MOST. Its performance were too coarse for measuring solar-like oscillations in solar-like stars (Matthews et al. 2004). The launch of the small mission CoRoT developed and operated by CNES has opened a new era in asteroseismology. Analysis of the initial run (March to April 2007) has proven that the specifications were met. Spectrometric ground-based observations, when conducted with a high duty cycle *and* a long duration are competitive and complementary to space photometric observations in many aspects:
- They give access to spherical harmonic $\ell = 3$ modes, whereas photometric observations are limited to $\ell = 2$. The measurement of $\ell = 3$ allows us to measure the small frequency separation between $\ell = 3$ and $\ell = 1$ modes.
- They are less affected by the low frequency noise related to stellar granulation or stellar activity. As in the solar case, this makes possible the measurement of low frequency modes.
- They give access to bright targets, that can be observed with other facilities, for a convergent better determination of primary parameters (effective temperature, gravity, abundances, radius).

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Table 1. Goals of asteroseismology

Age determination	Excitation mechanisms of convection	Rotation and internal structure
Stellar radius	Depth of convection	Depth of second helium ionization zones
Composition	Diagnostic of convective cores	

Table 2. For accurate modeling, asteroseismology observations require a frequency precision better than $0.2\,\mu$Hz. This translates directly into scientific specifications for the times series to be observed.

Continuous time series	Duty cycle $\eta \geq 80\%$
Long time series	Duration $T \geq 2$ months

- They give access to lower mass targets (including K stars).

The SIAMOIS project, a Fourier Tachometer at the Concordia station in Antarctica, is intended to meet the scientific goals (Table 1) thanks to its specifications (Table 2). The precise scientific case of SIAMOIS is developed in Section 2. The project is then briefly presented in Section 3, and the instrumental principle in Section 4.

2 Scientific case

The targets of the main program to be conducted with SIAMOIS will be selected by the scientific committee, among cool stars of G and K-type, on the main sequence or giant branch (Fig. 1). Each target will be tracked continuously for 3 months. In addition, less demanding targets will be observed, during periods when twilight and dawn may hamper the continuous observations (1 month each). These additional targets can be chosen among slowly-rotating high-amplitude classical pulsators, such as δ Scuti stars (main sequence, or PMS). The expected very high precision on the measurements of eigenfrequencies will allow us to tightly constrain the models of the interiors of these stars, extending to cooler stars the observational constraints brought by the CoRoT space mission. The much better S/N in the velocity data leads to more accurate frequency determination and the ability to detect modes of lower frequencies that buried in the noise in intensity observations. Both points are very important for structure inversion and asteroseismic investigation of stellar interiors.

2.1 Frequency analysis

The detection of solar p modes gained enormously from long observation. The main improvement was for resolved modes (mode with a lifetime shorter than the observation time) for which precision on the mode frequency increases like the square root of the observation time, i.e. an observation 4 times longer provides a frequency precision twice better (Libbrecht, 1992; Toutain and Appourchaux, 1994). Translated into structure inversions it directly provides a two-fold improvement in the precision. The signal-to-noise ratio for non-resolved modes (mode with a lifetime longer than the observation time) increases as the observation time to the power 3/2 (Koen 1999). In addition the number of detected modes will be higher with stellar radial velocities compared to those detected in intensity. As an example of the impact, comparison of structure inversion for the Sun obtained with GOLF (solar radial velocities looking at the Sun as a star) compared to that of VIRGO (intensity looking

Table 3. Current status of ground-based asteroseismic observations. Full references in Bedding & Kjeldsen 2006, completed with unpublished results (F. Carrier, private communication)

oscillation detection	about 20 targets
mode identification	about 12 targets
2-sites observation	6 targets
network observation	1 target: Procyon
stellar structure modeling	2 targets: αCen A and B
rotation, convection...	insufficient precision

at the Sun as a star) presents a gain greater than a factor 4 for some regions of the Sun, thanks to low-frequency modes that cannot be observed in intensity (Appourchaux et al 1997).

With SIAMOIS, 3-month long time series and the absence of day-night interruption (Mosser & Aristidi 2007) will give access to unprecedented precision in stellar structure compared to any other ground-based observations. Overall, the structure inversion will be significantly better with uninterrupted and longer time series, as demonstrated by the helioseismic community.

2.2 *Amplitudes*

For the Sun, it is possible for several years to measure independently the amplitudes and lifetimes of the detected p modes. These measurements enable us to compute the rates at which energy is supplied into the modes by turbulent convection, and hence to derive strong constraints on turbulent convection. They also provide constraints on the damping processes, mainly attributed to coupling between the modes and turbulent convection. Both mechanisms (excitation and damping) are still poorly modeled and need additional constraints to those obtained from helioseismology.

Current ground-based observations are not yet able to provide such constraints for asteroseismology. CoRoT will provide them for a large set of solar-like oscillating stars, but amplitudes determined from a photometric signal depend on the radiative losses of the oscillations in the outer layers of the star. The SIAMOIS Doppler signal, not sensitive to that effect, will yield a more precise determination of the amplitudes.

2.3 *Interior models: composition*

The observation of the exoplanet host star μ Ara (Bazot et al. 2005) gives an example of current limitations of ground-based oscillations. Stars with exoplanets present an average overmetallicity of about 0.2 dex compared to stars without planets (Gonzalez 1998; Santos et al. 2003), which may be due either to high initial metal content in the proto-stellar gas or to accretion of hydrogen-poor matter during the planetary formation process, or both. In the first case the stars should be completely overmetallic while in the second case the overmetallicity should be confined to the outer layers. For stars with masses around $1.1\,M_{\odot}$, there is a substantial difference between the two kinds of models: the completely overmetallic ones have a convective core while the accretion models do not. This difference could be detected from asteroseismology, through the small separations (Bazot and Vauclair 2004). Unfortunately, in spite of the very good SNR obtained with HARPS the precision on the eigenfrequencies available in single-site observation is limited and not sufficient to reach a clear conclusion.

A longer coverage with no diurnal interruption in the time series, such as only instruments like CoRoT and SIAMOIS can offer, is thus necessary to fully exploit the asteroseismic potential of stars with solar-like oscillations.

2.4 *Red giants*

Asteroseismology gives also a unique opportunity to probe the interior of evolved stars. Red giants differ from main sequence stars because of their large radii, their extremely dense cores and the fact that they are in the hydrogen-shell burning phase. Detection of solar-like oscillation has been reported in few red giants (e.g. Frandsen et al. 2002, de Ridder et al. 2006). These stars have in fact an external convective envelope, where the excitation is located. They show oscillation amplitude of the order of few $\mathrm{m\,s^{-1}}$ (about 20 $\mathrm{cm\,s^{-1}}$ for the Sun) and oscillation period of the order of few hours (around 5 min for the Sun). Despite the successful detections of solar-like oscillations mentioned above, the physical interpretation remains limited. Higher duty cycle and a longer time coverage are needed to fully exploit the seismic data. The recent results obtained by the MOST satellite on these kind of stars demonstrate the promise of extended time coverage and high duty cycle for red giant targets.

The gain in time coverage and in duty cycle obtained with SIAMOIS will allow us to make a big step forward for the seismic study of this kind of stars.

2.5 *Delta Scuti*

δ Scuti pulsators are variable stars representative of intermediate mass stars (1.5-2.5 $M_{\odot}$) in the Pre-Main Sequence, Main Sequence, and slightly Post-Main Sequence phases (Hydrogen shell-burning phase). They thus constitute ideal targets to study physical key-processes driving the main sequence phase (90% of the stellar life time), the initial conditions inherited from the PMS phase, and the dramatic phase ending the main sequence phase, when core hydrogen exhaustion induces rapid and important changes in the structure of the stars on their way to the red giant branch. Among these key-processes, one can cite transport of angular momentum, of chemical species via large scale circulation vs gravitational settling balance, inertial extension of the chemical mixing beyond the classical limit of the convective core (overshooting process) with dramatic influence on the evolution time and age determination. Although these objects are traditionally fast rotators, several objects exist, showing low enough $v \sin i$ to constitute good targets for spectrometric measurements.

For most of these objects, the expected noise level with SIAMOIS is much less than 10 $\mathrm{m\,s^{-1}}$, which is ten times better than what is currently achieved in spectroscopy for these objects (see e.g. ρ Pup, Mathias et al. 1997). In addition to this, the continuity and the duration will be a great advantage to help resolving beating modes, when the theoretical spectrum is too dense to be resolved by classical observations spanning only 2 or 3 weeks.

2.6 Gamma Doradus

γ Doradus stars are g mode pulsators, located on the main sequence between A7 and F5, and having periods of typically 1 day. Compared to the other groups of g mode stars, they are much more numerous and bright, rendering their study easier. Moreover, being close to the Sun on the Main Sequence, and although their envelope structure differ from solar, the studies of γ Doradus stars can bring new insights into the structure of the deeper layers.

Spectroscopic studies show that rotation does not inhibit pulsation, since $v \sin i$ values for these stars vary between a few $\mathrm{km\,s^{-1}}$ and more than 100 $\mathrm{km\,s^{-1}}$. Therefore, many low $v \sin i$ pulsators can be easily proposed as targets. The typical amplitudes are a few 100 $\mathrm{m\,s^{-1}}$, which correspond to the actual detection threshold for such targets. No doubt that lower amplitude modes will be detected with SIAMOIS.

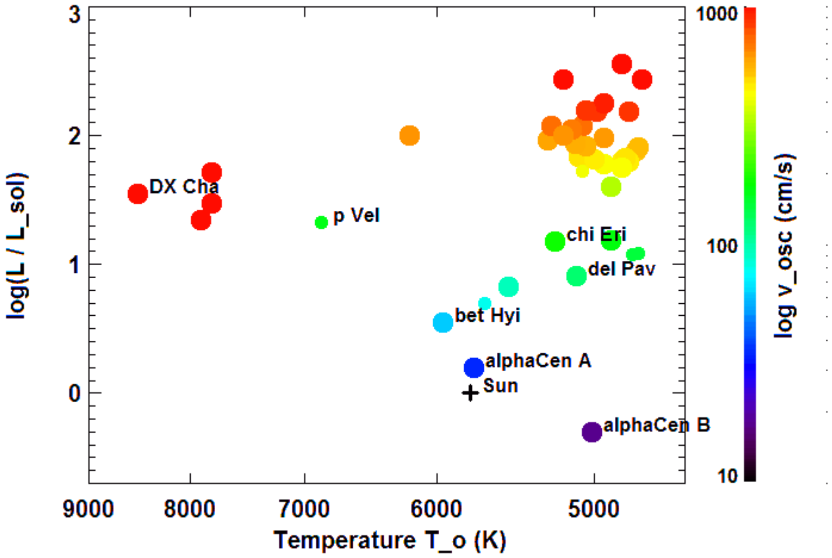

Fig. 1. HR diagram with observable targets at Dome C with SIAMOIS, with a SNR better than 6 after 5 days and 90% duty cycle. The maximum expected oscillation amplitudes are derived from Samadi et al. 2003. For clarity, large amplitudes have been truncated at 10 $\mathrm{m\,s^{-1}}$. Numerous giant targets are available, as well as low rotation δ Scuti, γ Dor or PMS (only a few examples are shown). The position of the Sun is only given as a reference.

Table 4. Schedule of SIAMOIS (with expected funding in 2008 for phases $\geq$ B)

2006	thermo-mechanical analysis
2007	phase A study completed ,PDR
2009	FDR
2010	integration, tests
2011	summer campaign: Dome C
2012	First winterover at Dome C

3 Project

A pioneering astronomy project at the Concordia station in Dome C has to be an integrated project. It has to be fully tested in laboratory as well as in real observing conditions before setup at Dome C. This setup has to be very simple, and cannot require sophisticated installations and extensive personnel. The whole instrumentation has to be fully automatic. Its operation has to require very limited human control, and principally remote control from the main building at Dome C. In many aspects, such a project must be managed like a space project. However, in contrast to a space project, human action is possible for routine supervision, as well as for rare, simple and necessary work related to the survival of the instrument in the drastic conditions of Antarctica. Note that these operations can be very simple, but necessary: for example, wipe out a few mm of snow.

Accordingly, the specifications of SIAMOIS converge with these requirements.

- The scientific programme is simple and stable, with 3-month long observing of the same target at maximum duty cycle, plus 1-month long observations before and after the period of total night on several additional targets requiring a less stringent duty cycle.
- The small collector (40 cm) to meet the requirements in the Dome-C environment will be developed in parallel by the A-Step project (funded by ANR). The schedule of the A-Step project (first light in 2008) will permit SIAMOIS to benefit from its experience.
- The fiber-fed instrument will be installed in a heated container. The instrument will therefore not be subject to the drastic Antarctic conditions, and tests will be performed in usual thermal conditions.
- The interferometer is designed as a monolithic piece of glass (zerodur). Its high reliability insures the required stability throughout its life. It will be transported independently of the rest of the instrument. Its support is designed for rapid installation, requiring only standard optical conditions for accurate imaging, and nothing demanding due to interferometric requirements.
- The data flow is limited. Spectra will be reduced automatically in real time. The time series will be transferred every day to Europe.
- The on-site supervision of the instrument is estimated to less than 20% FTE during the wintering.

The time line of SIAMOIS is presented in Table 4.

4 Instrumental principle

Applied to the Sun in the 1980's, Fourier Tachometry was chosen for the GONG helioseismic network after a long study of competing measurement strategies (`http://gong.nso.edu`), and it forms the basis of the Michelson Doppler Imager instrument on the SOHO spacecraft as well as the Velocity and Magnetic Imager on the forthcoming SDO spacecraft. The data analysis is extremely simple: the sine-wave fit yields an amplitude (essentially the strength of the line), a mean value (the average intensity), and a phase (the Doppler shifted wavelength of the center of gravity of the line).

The principle and performance of a dedicated efficient instrument for asteroseismology are described in Mosser et al (2003), optimized according to the experience with the step-by-step FTS at CFHT, with results on Procyon and Jupiter (Mosser et al 1998, 2000). As opposed to a classical FTS, the FT seismometer works without any moving parts (Maillard et al 2003). The working path difference is produced by a plane parallel plate in one arm of the interferometer and sampled by five $\lambda/10$ steps (with λ about 500 nm) made on the surface of one mirror of the interferometer. With this technique a fringe of the interferogram is defined by 5 samples. The phase of this fringe gives directly the Doppler signal. Efficiency is increased by additional post-dispersive optics, dividing the spectral range (400 to 560 nm) in about 340 spectral elements. This post-dispersion gives an increased fringe contrast for each spectral element, and boosts the photon noise limited performance by a factor of 7. In parallel, a spectral calibration source gives a reference spectral signal for all the acquired spectra and allows correction of the signal.

The interferometer is fed by an optical fiber connected to the collector. A specific system included inside the collector and called a "bonnette" controls the motion of the collector to insure the accurate injection of the light inside the optical fiber. This bonnette is equipped with an internal calibration system (flat-fielding). All the subsystems (collector/bonnette, interferometer, camera...) will be electrically connected to the command/control system (acquisition, setup parameter, data processing). As an option, we propose to include a second 40-cm telescope in the design, and to feed the interferometer with two separate fibers, each from one of the two collecting telescopes. Both telescopes are pointed simultaneously to different stars, thus doubling the scientific output of SIAMOIS for a limited cost. Such simultaneous observations of two stars with two telescopes require only the stellar magnitudes and rotation rates to be similar.

5 Conclusion

SIAMOIS is the first ground-based project ensuring the essential property of asteroseismic observations: long and uninterrupted time series. Six winters with SIAMOIS will provide 6 long runs (3 months) with a duty cycle about 90% on 6 bright targets, plus 12 runs (1 month) on secondary targets (red giant, δ Scuti, γ Dor, β Cep, PMS...) with a duty cycle better than 60%. With a second telescope, the number of targets will be doubled. The instrument is in fact initially designed to be fed with 2 scientific fibers, each fiber being coupled to a given telescope, for the simultaneous observation of 2 stars. Compared to current ground-based observations, the gain is duty cycle and frequency resolution will provide very precise eigenfrequencies measurements, with a precision increased by a factor better than 5 compared to the rare available measurements. This translates to the same gain in precision for structure inversion. Modes amplitudes and lifetimes will be measured with an unprecedented precision. Spectrometric measurements with SIAMOIS will yield complementary observables and measures to the CoRoT photometric observations. The better S/N in the velocity data obviously leads to more accurate frequency determination, especially at low frequency, for accurate stellar inversion.

References

Appourchaux et al. 1997. Proceedings of the 181st symposium of the IAU, held in Nice, France, September 30 - October 3, edited by Provost & Schmider. Dordrecht Kluwer Academic Publishers, p.159

Bazot, M., Vauclair, S., 2004. A&A 427, 965

Bazot, M., Vauclair, S., Bouchy, F., & Santos, N.C. 2005. A&A 440, 615

Bedding T, Kjeldsen H 2007. CoAst 150, 106

Bedding et al. 2004, ApJ 614, 380

Bouchy, F., et al. 2005. A&A, 440, 609

Frandsen, S., et al. 2002, A&A, 394, L5

Gonzalez 1998 A&A 334, 221

Koen 1999, MNRAS 309, 769

Libbrecht, 1992, ApJ 387, 712

Maillard JP, B. Mosser, J.M. Reess, 2003 in Fourier Transform Spectroscopy, OSA Topical Meeting, 2003 Technical Digest, p. 189

Mathias et al. 1997, A&A 327,1077.

Matthews J et al 2004. Nature 430, 51

Mosser, B.; Maillard, J. P.; Mkarnia, D.; Gay, J 1998. A&A 340, 457

Mosser, B.; Maillard, J. P.; Mkarnia, D. 2000. Icarus 144, 104

Mosser, B.; Maillard, J. P.; Bouchy F. 2003. PASP 115, 990-1001

Mosser & Aristidi 2007. PASP 119, 127

de Ridder, J.; Barban, C.; Carrier, F.; et al 2006. A&A 448, 689

Samadi R et al. 2003. A&A 404, 1129

Santos et al. 2003 A&A 398, 363

Toutain, T.; Appourchaux, T. 1994. A&A 289, 649