Session 4. Interacting Binaries and Pulsating Variables

Convener: Prof. Ivan Andronov (ONU, Ukraine)

ASTEROSEISMOLOGY: A CHALLENGE FOR INTERNATIONAL COLLABORATION [1]

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Asteroseismology is rather new diagnostic tool for investigating the interior and evolutionary status of stars. The potential for testing stellar models is already successfully demonstrated for our sun. Helioseismology, *e.g.*, allowed to investigate the rotation in the solar interior, the settling of helium, mixing and overshooting effects at the bottom of the convection zone, vertical extensions of active regions and to monitor them also on the hemisphere not visible from ground.
Of the various groups of pulsating stars, asteroseismology has been successfully applied to subdwarf B-type stars (sdB), pulsating white dwarfs (DA and DB), and to some extent also to rapidly oscillating Ap (roAp) stars. It has not yet been possible to model the observed pulsation frequency spectra of δ Scuti stars to satisfaction (*e.g.*, FG Vir), but experts expects a break-through in the near future, at the latest when observations from space will be available. γ Doradus and λ Bootis stars share this situation, and to some extent also β Cephei and the Slowly Pulsating B-type (SPB) stars. For the latest reviews in this field consult [1].
Two satellites, specialized for high precision photometry, will be launched in the next years, MOST in 2002 and COROT in 2004. A third one, the ESA mission EDDINGTON, has good chances for a launch around 2010, and the Danish project MONS is in a study phase.

POTENTIAL AND PROBLEMS OF ASTEROSEISMOLOGY

Many stars (*all* stars ?) pulsate with amplitudes ranging from about a magnitude to a thousandth of a magnitude or even less. Fig. 1 shows the Hertzsprung-Russell diagramme based on the HIPPARCOS observations plotted together with various classes of pulsating stars (ESA-SCI(2000)8).

Oscillations of stars are determined by their internal dynamics and structure. A precise determination of pulsation frequencies, therefore, allows to derive information about the interior of stars and the evolutionary status. This technique is called asteroseismology and its importance for modern astrophysics can be compared to that of X-ray techniques for medical or material sciences.

Asteroseismology can be defined as a method of testing stellar structure and evolution theory, using all available pulsation data, including also growth rates, phases, the fact that mode exists, and sometimes are transient, *etc.* [2]. In the present status of theory, a stellar model is typically characterized by five parameters (mass, age, initial compositions in helium and metals, and mixing length – a parameter describing the convective transport of energy) for which we usually have only two observables (effective temperature and surface gravity). Consequently, stellar models cannot be adequately tested without introducing additional assumptions. Moreover, we have some reasons not to trust our description of stellar interiors.

When open clusters or binary systems are observed for which independent constraints on some astrophysical parameters are available (same age and same initial composition for each star in the ensemble), it is usually impossible to reproduce the observed properties of the stars with the same value of the mixing length. This

Invited paper.
[1] Dedicated to Prof. Karl D. Rakosch, the pioneer of space astronomy in Austria, at his 75th birthday.

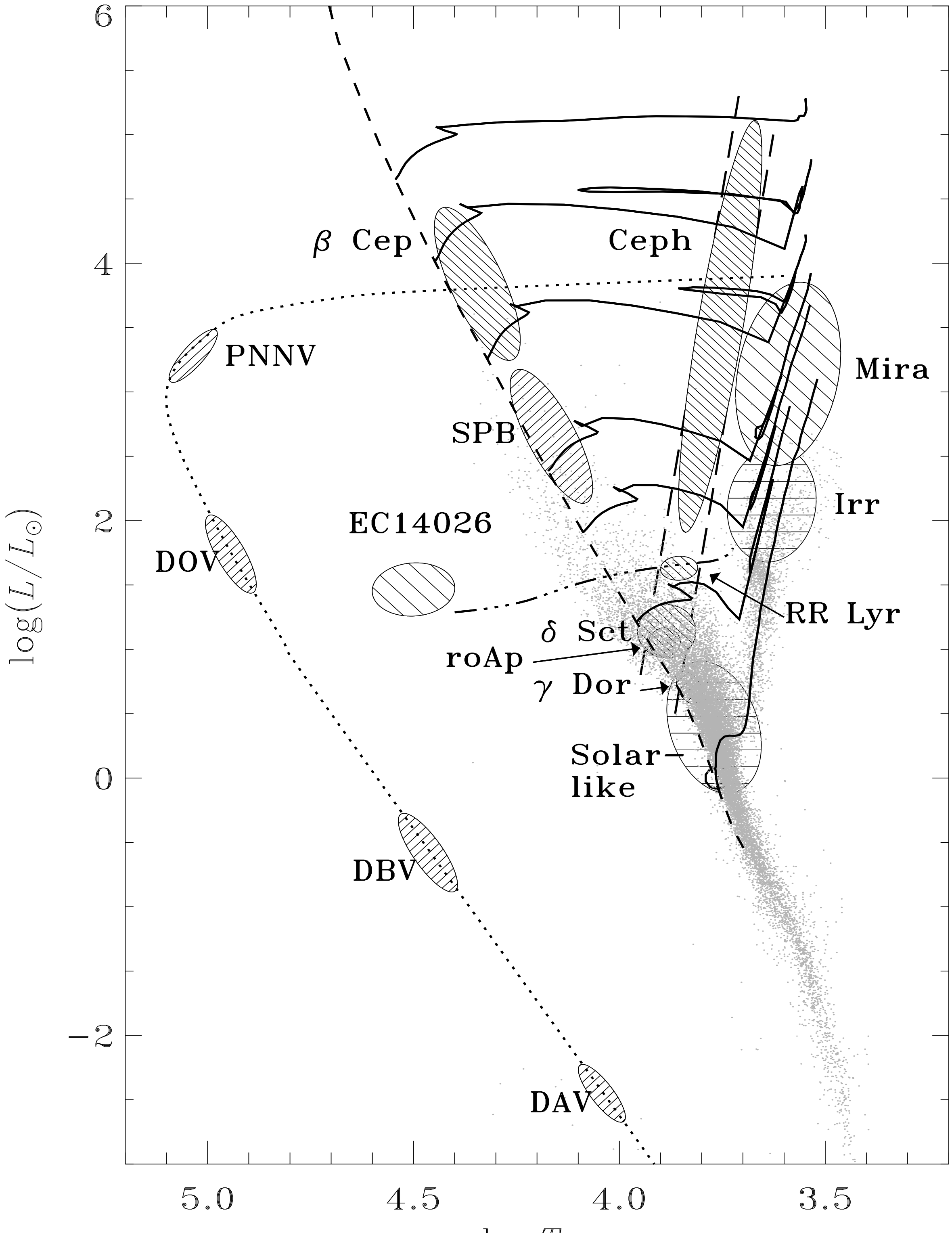

Figure 1: Schematic location of various classes of pulsating stars in the Hertzsprung-Russell diagramme, plotted together with the HIPPARCOS observations (ESA-SCI(2000)8)

confirms that the representation of convective transport by the mixing length theory is not adequate. This is only one example of many others which illustrate that an improvement of stellar modelling is clearly necessary. However, such an improvement is possible only if adequate tests for current models can be provided. Asteroseismology is this new tool for this purpose.

Pulsating stars have already been known since 1784, when δ Cephei was discovered as a variable star. It took nearly 200 more years to understand the reasons for this type of stellar variability. A more recent example for observations of a pulsating star, the λ Bootis star 29 Cyg, is presented in Fig. 2. The data were obtained during an international multisite campaign in 1997.

Eigenmodes of pulsations carry a wealth of information on the state of the interior of stars. A mode of

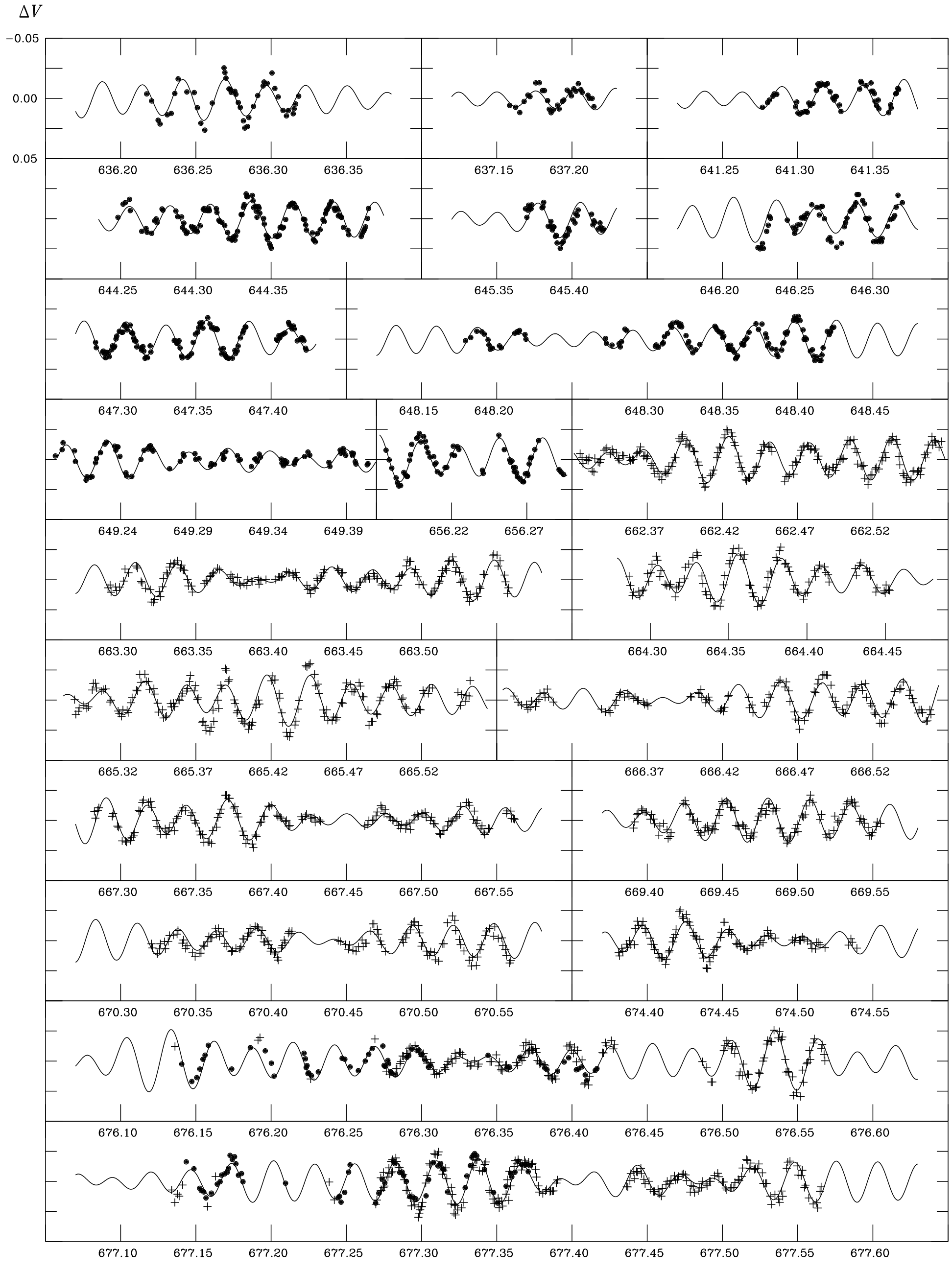

Figure 2: Photometric light curve for 29 Cyg obtained during a multisite campaign in 1997 with 5 observatories in America, Europe and Asia participating

a given degree ℓ and order (overtone) n is confined to a given cavity within the star. High degree modes are restricted to sub-surface layers, while low degree modes propagate all the way to the center of the star. Surface harmonics, $Y_{\ell,n,m}$, usually help to describe the oscillation modes, where the azimuthal order m is degenerate for a spherical symmetric star.

So far, the method seems to be fairly simple. Given is a set of the observed frequencies and one has "only" to find a model which reproduces these frequencies within the errors. The limits of this approach are quickly evident, if evolved and rotating stars are investigated, as it is shown in Fig. 3 for the two λ Bootis stars HD 111786 and HD 142994 [3]. Obviously, it is impossible to identify ℓ, n and m clearly for the modes observed with the given frequencies. Without knowledge of these parameters an inversion is impossible and asteroseismic techniques cannot be directly applied.

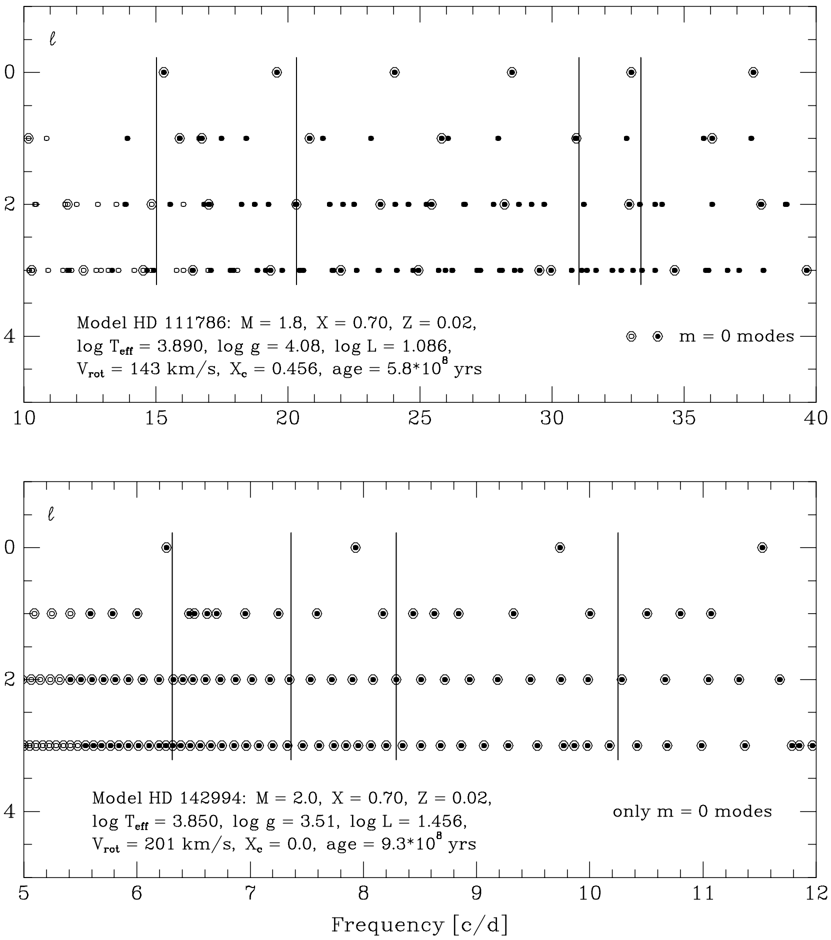

Figure 3: Computed frequency spectra of low-degree oscillations including frequency shifts due to rotation. Horizontal sets of points correspond to fixed values of spherical harmonic degree. Filled circles mark unstable modes. Vertical lines are the observed frequencies [3]

Stellar rotation and evolution of stars are not the only ingredients which affect stellar models and hence the observable frequency spectra. Physical effects which render the application of asteroseismic techniques difficult, *e.g.*, are convection in the stellar envelope, core overshooting, hydrogen abundance, and heavy element abundances. An excellent review on this subject for δ Scuti stars is given in [4].

REQUIREMENTS FOR AN ASTEROSEISMIC ANALYSIS

Concluding the previous section, we identify the following problem. A direct mode identification is very difficult, because there are too many free parameters to fit relatively few frequencies. The following remark made by W. Dziembowski [5] sounds very pessimistic: *...without understanding mode selection we will never be able to make use of non radial mode frequencies for seismic probing...*

But what can be done to win the race against the odds? The asymptotic theory shows [6] that certain pattern can be expected in the frequency spectrum of a star which is pulsating in several modes, if $\ell \ll n$. Basically, one finds frequencies separated by the so-called "large separation", Δ, which for solar like stars typically ranges between 100 and 150 μHz, and the "small separation", δ, ranging from few to 20 μHz. Δ is inverse proportional to the sound travel time across a star and hence is sensitive to the global properties. δ, on the other hand, is proportional to the gradient of the sound speed weighted with the distance to the surface. Therefore, this quantity is sensitive to the interior of a star close to the core and hence also depends on the age. For our sun, data obtained from space by, *e.g.*, IPHIR or VIRGO, or from ground by BISON, IRIS or GONG, clearly show these periodicities (*e.g.*, [7]).

In conclusion, information about the structure of a star can be deduced from a pulsation frequency spectrum even without identifying individual modes, provided that characteristic frequency *pattern* can be determined.

In the case of a frequency identification close to the noise level, it can be helpful if the so-called combination modes can be identified in the frequency spectrum. These combination modes with frequencies $f = f_i \pm f_k$ are not observational artifacts but intrinsic to the star [8]. These modes, however, are expected at low frequencies what requires a very stable instrument for detection, and at high frequencies, requiring short integration times.

A further help for proper mode identification can come from multicolor photometry of pulsating stars. The amplitude and phases of light and color variations obtained with properly chosen filters can be related to luminosity and temperature variations due to pulsation. A phase lag between temperature and luminosity variation can be helpful for a mode identification.

Finally, if higher pulsation orders, ℓ, can be observed, different parts of the stellar interior can be analyzed and hence the choice of models can be restricted.

In conclusion, there are indeed some possibilities to apply asteroseismic techniques, even if a direct mode identification is not possible. The requirements for the needed observations are following:

- low noise of the pulsation frequency spectrum
- large frequency range
- high frequency resolution
- supplementary observations from ground, in particular spectroscopy
- restriction of the number of free parameters

what can be summarized in the popular saying: *The best possible may be barely sufficient.*

The low noise is important, because we want to detect a sufficient number of frequencies for deriving the characteristic frequency spacings. As the amplitudes tend to decrease outside a characteristic frequency range, the detection threshold has to be quite low in order to identify these additional frequencies in the noise.

Asteroseismic information is buried in a large frequency range, if also combination modes are considered. To obtain reliable data in such a large range requires an extremely stable instrument in an excellent observing site. This is a rather rare combination.

For identifying frequency splitting due to, *e.g.*, rotation or a magnetic field, a high frequency resolution is needed, which means long and uninterrupted observations. Large gaps in the data result in a poor "window" function which increases the noise level and ambiguity in the identification of correct frequencies.

Whereas photometry is sensitive to low order modes, because we integrate over the visible stellar hemisphere, spectroscopy allows to observe higher orders. Due to the Doppler effect the various velocity fields on the stellar surface appear as wavelength shifts in spectral line profiles. Hence, spectroscopy is a very important complement to photometry of pulsating stars.

We have already mentioned earlier that presently stellar models typically are characterized by mass M, age t, initial compositions in helium Y and metals Z, and α – a parameter describing the convective transport of energy. To determine these quantities we usually have only observables which have to be extracted from spectroscopic and photometric observations of the stellar atmosphere, like temperature T, metallicity Z, and surface gravity g, and also the parallax p for nearby stars. Consequently, stellar models in general cannot be adequately tested and additional information is needed, like that obtained from pulsation frequency spectra of oscillating stars, which carry information about the internal physical conditions of stars.

Asteroseismology of members of star clusters or multiple stellar systems has the advantage of similar parameter values for all the pulsating stars in the ensemble, like age, metallicity or the MLT parameter α. Unfortunately, suitable clusters are already quite faint for the telescopes available for typical ground based multisite campaigns of many weeks.

TOWARDS NEEDED DATA

The observational requirements needed for a determination of a rich pulsation frequency spectrum have been listed in the previous section. How to obtain these data?

The photometric noise can be reduced by increasing the number of registered photones (more observations, larger telescopes), whereas the scintillation noise can be reduced by using large telescopes (4-m class and larger). A total elimination is only possible by going to space. Another annoying noise source are large gaps in the data. A poor window function increases the noise level in frequency space and due to the aliasing problem it increases the danger of misidentification of intrinsic frequencies.

To obtain reliable data in a large frequency range requires extremely stable instrumentation, access to observing sites with a very homogeneous atmosphere – or to go to space.

A high frequency resolution can only be achieved with a long time base of the observations. There are two strategies possible. Either to organize international observing campaigns with participation of observatories distributed over all continents, or to obtain the data from a spacecraft with an appropriate orbit. Both strategies are followed at our institute. The δ Scuti network (M. Breger *et al.*) also in combination with WET (Whole Earth Telescope: D. Winget *et al.*) or CAN (Central Asian Network: D. Mkrtichian *et al.*) provided already excellent data sets. The other strategy is to participate in the development of space experiments dedicated to high precision photometry, where the author is involved in COROT, MOST and EDDINGTON. In any case, a substantial international collaboration is needed for networks as well as for space experiments.

At this point it should be mentioned that probably no pure asteroseismic space mission would have been funded, if not the search for terrestrial planets circling around stars other than our sun would not have had similar technical requirements: a continuous high precision photometric monitoring of stars over many months and up to few years.

In the following we briefly will describe the mentioned space experiments.

COROT: COROT stands for *CO*nvection, *RO*tation and *T*ransits. This mission currently is in phase C/D and is a project of the French space agency, CNES, with bilateral cooperation of Austria, Belgium, ESA, Italy, and Spain. It will realize both a first exploratory step, to detect oscillations in a large variety of stars to classify the asteroseismic properties of stars in the HR-diagramme and a more specific one, centered on a detailed study of a few objects, specially chosen to test the hydrodynamics of the internal layers and the physical state of the stellar cores.

An exploratory programme will determine the domain of stellar parameters for which oscillations are detectable, and will investigate the relation between the amplitudes of the solar-like oscillators and their astrophysical parameters. Though several theoretical predictions of the amplitudes of oscillations excited stochastically by convective motions exist, a large uncertainty remains, in particular on the treatment of the superadiabatic external layers and on the scaling of the turbulent velocity field.

To match the scientific goal of COROTs exploratory programme one has to observe a sample of objects with a variety of stellar parameters, *i.e.*, mass, age, chemical composition, state of rotation, *etc.*, but only a moderate signal to noise ratio is needed. A substantial ground based support programme has been developed to provide information on most of these parameters for the target star candidates, primarily based on spectroscopic observations. A frequency resolution of $0.5\,\mu$Hz is sufficient for the exploratory programme, corresponding to observing runs of 10 to 20 days. Stars down to the 9th magnitude are appropriate targets; 5 to 10 targets will be observable at the same time. Several tens of stars will have to be checked, corresponding to a total observing time within the exploratory programme of at least 2 to 4 months. Up to now COROT is the only project which is able to observe several (ten) stars simultaneously in its seismologic mode.

The so-called Central Programme is more ambitious and more time consuming than the exploratory one, it corresponds to the second step in the development of space asteroseismology and aims at observing very precisely a small set of objects, selected for their diagnostic power. The choice of these targets will be partly based on the results of the exploratory phase. Based on the solar case, the accuracy of the frequency measurement is chosen to be $0.1\,\mu$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, the detection threshold will be less than 1 ppm. For A and F type stars close to the main sequence, it will then be possible to measure the size of the convective cores, the size of the outer convective zones and their helium content or the rotation profile of δ Scuti stars.

A least 5 runs, each about 150 days long are planned, during which one bright star (the main target) and a few stars in the surrounding field of view will be followed.

The Institute for Astronomy is participating in the development of a flight hardware thanks to a substantial research grant of the Bundesministerium für Unterricht, Wissenschaft und Kultur (BMUWK). This grant covers only the expenses for our hardware contribution and the scientific activities have to be funded through the Fonds zur Förderung der wissenschaftlichen Forschung (FWF).

COROT is scheduled for launch in the year 2004.

MOST: MOST (*M*icrovariability & *O*scillations of *ST*ars) is a Canadian project currently in phase C/D and with a possible Austrian participation. The scientific aim is to perform seismology of sun-like and magnetic stars from space, as well as to study microvariability in Wolf-Rayet winds and other pulsating targets. The main scientific goals of MOST are, therefore, similar to COROT.

A 15-cm Maksutov telescope is mounted on a micro satellite bus only 50 kg in mass and with dimensions of about 60×60×24 cm. The microsat will be launched into a polar sun-synchronous orbit ≈ 800 km high, as a secondary payload (possibly aboard a Delta rocket with Radarsat II). From that vantage point, MOST will be able to monitor certain stars in Continuous Viewing Zones for up to 7 weeks without interruption. The satellite will be stabilized by a set of miniature reaction wheels which will point the telescope to an accuracy of about 10 arcsec. This sounds like poor tracking, but until now, any microsat of comparable size could only be stabilized to within 2 – 3 degrees! The current design is expected to reach photometric precision of better than a few micro mag in stars as faint as V = 6 in about ten days of observation. Launch is expected for 2002. It is very pleasing to mention here that a former student of our institute, Dr. Rainer Kuschnig, serves as the instrument scientist for MOST.

EDDINGTON: This is an ESA F-type mission which will be developed parallel to the NGST (New Generation Space Telescope) project and was selected in October 2000. The EDDINGTON mission has two primary goals (ESA-SCI(2000)8), similar to COROT and MOST, to provide data on the evolution and age of stars using asteroseismic techniques, and to find habitable planets outside of our solar system using the transit method.

The lifetime of EDDINGTON will be divided into two phases, one dedicated mainly to asteroseismology (the first 2 yrs of the mission) and the other mainly to planetary transit detection (the following 3 yrs of the mission). Each of the two primary science goals will, however, continue throughout the whole mission's lifetime, although they will have a lower priority when the other science is "prime".

Thanks to its large field of view, EDDINGTON will acquire data simultaneously on a large number of targets: asteroseismic data will be collected on some 50 000 stars, while planetary transits will be searched for on some 700 000 stars. Also, its larger collecting area will allow it to observe crucial stages of stellar evolution which are not available among the bright stars in the sky. These facts will allow EDDINGTON to achieve

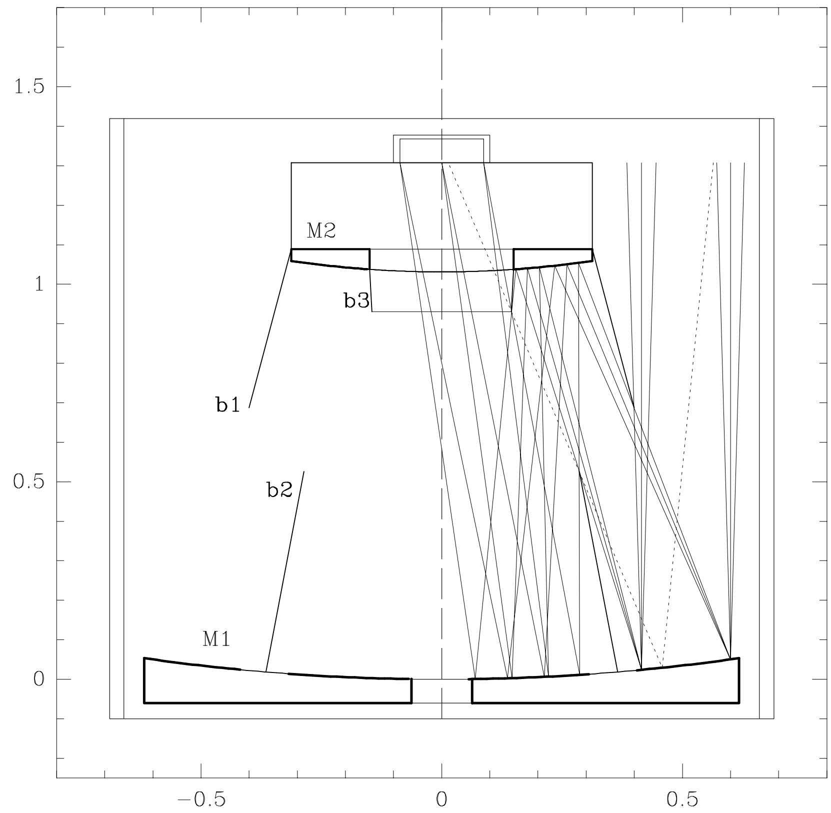

Figure 4: Optical scheme of the EDDINGTON three mirror system

qualitatively different science goals than the small national projects (COROT, MONS, MOST) which are currently under development and which can be considered at some level as its precursors.

In addition, to the two primary science goals, the EDDINGTON data will allow several other scientific programs to be carried out, both in the field of stellar physics as well as in the field of galactic dynamics and evolution.

EDDINGTON features a simple, single payload: a lightweight, wide field-of-view 1.2-m diameter optical telescope, with twin mosaic CCD cameras (Fig. 4). The key requirement imposed on the mission by the observing program is one of long, uninterrupted observations, thus favouring deep orbits – L2 being currently the one base.

The launch date is expected between 2007 to 2013, depending on the development of the ESA Science programme.

MONS: MONS was selected in August 1998 to undergo a pre-Phase A study under the Danish Small Satellite Programme (DSSP). A proposal was submitted on April 1, 1999, and currently it is studied in a merged version with BALERINA, a mission dedicated to observe γ-ray bursters.

MONS will measure oscillations in about 25 nearby stars by monitoring the brightness and color fluctuations in each star for about one month. The spacecraft has overall dimensions of $60\times60\times80$ cm, a mass of 65 kg, and a power budget of 60 W. The orbit is elliptical with a high apogee, to allow (i) almost continuous observations of each star, and (ii) access to the whole sky during the course of a year. The baseline is a Molniya orbit, with a high inclination that will minimize radiation exposure, with a mission lifetime of two years.

The attitude control system will be 3-axis stabilized, with a required precision of about 0.02 degree rms (1.2 arcmin). This will be achieved using momentum wheels, with attitude sensing via two wide-field star imagers. The star imagers will also serve as secondary scientific instruments, providing photometry for about 10 000 stars over the mission.

The telescope is a 34-cm reflector, with a dichroic beamsplitter to form side-by-side blue and red stellar images. Each stellar image is highly defocussed to avoid saturating the CCD detector and minimize sensitivity to attitude movements.

Data frames will be taken every 4 seconds and on-board data processing will measure the brightness of stars every 20 seconds. The down-link rate, including house keeping, will be below 4 Mbyte per day.

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