Asteroseismology

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Introduction

Probably the most convincing definition for what *asteroseismology* actually is, was given by Däppen, Dziembowski and Sienkiewicz (IAU Symp. No. 123, p. 233, 1988) 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.), and not just observed frequencies.

Asteroseismology probably opens the accessible parameter space well beyond the classical instability strips, if solar-type oscillations can be observed for a large variety of stars. It has become an increasingly accepted opinion that pulsation (probably mostly in the form of non-radial pulsation) is the rule, rather than the exception. Unfortunately, the observable quantities tend to be extremely small and new instrumentation is needed, for ground-based observations as well as for observations from space. The prospects, however, are magnificent since it appears to be possible to test stellar interior and evolution over most of the parameter space of the HR diagram. Stars where relativistic effects are not important and which might therefore be classified as 'normal', will probably serve as most common targets for asteroseismology.

'Normal' stars are very interesting astronomical objects in themselves and certainly are not 'boring'. They play a crucial role in the chemical evolution of the Universe. Stars on the Main Sequence and close to it are by far the most frequent and easily observable ingredients of the Universe. All our understanding of the Cosmos is based on calibrations (age, distance, mass, etc.) obtained from our closest neighbours. We will not be able to appreciate our Cosmos until we fully understand its constituent stars. Understanding stellar evolution is fundamental for a coherent picture of the Universe, because the life of galaxies largely depends on the life of their basic, luminous constituents: the stars.

For many years, astronomers have struggled with the problem posed by these 'simple' objects, but find themselves still far from the goal anticipated by Eddington who, in 1926, finished his book on *The Internal Constitution of the Stars* with the sentence: ". . . but it is reasonable to hope that in a not too distant future we shall be competent to understand so simple a thing as a star."

These 'normal' stars are best suited for significant tests for various aspects of fundamental stellar physics. Confronting realistic stellar models with high-quality observations will tell us much about the underlaying physics.

In addition, stars constitute essential laboratories for studying important aspects of basic physics (convection, MHD, nuclear reactions, equation of states, transport processes, etc. . . .) under conditions which cannot be reproduced in terrestrial laboratories. For extremely high and low temperatures and densities, this stellar laboratory is indispensable for testing physical theories. These are just a few examples for the significance of stellar physics to what may be called laboratory physics.

Not surprisingly, many international conferences have been devoted in recent years to helio- and asteroseismology. IAU Colloquium No. 137 (Vienna, April 13 to 17, 1992) will be devoted, among others, to aspects raised in the present article and is entitled "Inside the Stars".

A short overview over the last 30 years of stellar astrophysics illustrates the immense increase of knowledge about how stars are working, but also about the serious shortcomings in our physical concepts and accuracy of our data.

In the sixties, a very important step in stellar modelling was achieved by qualitatively explaining the structure of the HR diagram at the level of accuracy of the observational data. In the late seventies and in the eighties the development of solar neutrino astronomy as well as helioseismology showed that there is not yet a satisfactory model which can predict the observed quantities at the very high level of accuracy meanwhile achieved. The immense progress in this field, accelerated by successful space experiments, suffers from a lack of generality, as was demonstrated, e.g., at IAU Colloquium No. 121, "Inside the Sun". New steps forward are needed to constrain theories by studying stars with different physical parameters (effective temperature, luminosity, chemical composition, rotation rate, magnetic fields, etc.).

In the nineties, still more accurate observational techniques are being developed which are suited to challenge theories in a parameter space more complex than the two-dimensional HR diagram. The most prominent new tools are:

- precise distances, measured by the Hipparcos satellite,
- pulsation periods, observed with ground-based telescope networks and with space experiments,
- rotational velocities and magnetic fields, derived from surface imaging techniques,
- new powerful detectors which help to increase the S/N of observations significantly,
- dramatic advances in computer technology.

Scientific Goals

The key issue of asteroseismology is the theory of stellar structure and evolution. In the present status of the 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 (luminosity and surface gravity). Consequently, stellar models cannot be adequately tested. Moreover, we have some reasons not to trust our description of stellar interiors. Let us take two examples.

- When ensembles of stars (like 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 may indicate that the representation of convective transport by the mixing length theory is not adequate.
- The observed solar neutrino flux is much lower than expected, which indicates that modelling of the solar interior is incomplete.

Already these two examples demonstrate that an improvement of stellar modelling is absolutely necessary. However, such an improvement is possible only if adequate tests for current models can be provided. Asteroseismology is a new tool for this purpose.

Pulsation

Classical pulsating stars have already been known since 1784, when δ Cephei

Figure 1: *Solar p-modes, equatorial cross section $l=40$, $m=40$, $\nu=3.175$ mHz.*

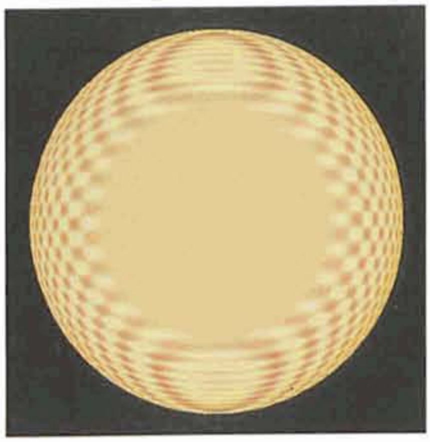

Figure 2: *Solar p-modes, equatorial cross section $l=40$, $m=0$, $\nu=3.175$ mHz.*

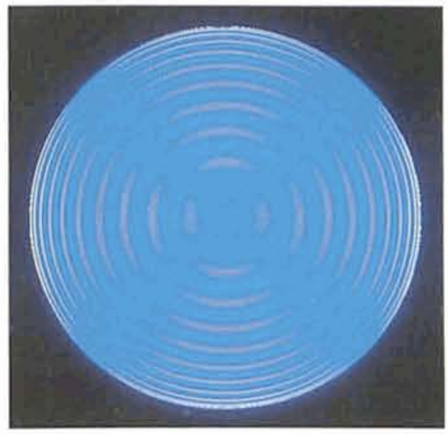

Figure 3: *Solar p-modes, equatorial cross section $l=2$, $m=2$, $\nu=3.147$ mHz.*

was discovered as a variable star. It took nearly 200 more years to understand the reasons for this type of stellar variability.

Eigenmodes of pulsations carry a wealth of information on the state of the interior of stars. A mode of a given degree l is confined to a given cavity within the star. High-degree modes, like the one represented in Figures 1 and 2, are restricted to sub-surface layers, while low-degree modes, as shown in Figure 3, propagate all the way to the centre of the star. The Figures 1 to 3 are equatorial cross sections through vibrating solar models and have been kindly provided by S. Frandsen (Astronomisk Institut, Aarhus). Amplitudes of the displacement vectors of the solar p-modes are colour coded. Another illustration of non-radial pulsation modes is given in Weiss and Schneider (*The Messenger*, No. **33**). For distant stars, ony low-degree modes can be detected because of the lack of spatial resolution. Fortunately, these modes are precisely those that probe the structure from surface to centre.

The roots of asteroseismology are, of course, the same as for the theory of classical pulsating stars. This can be best illustrated in the asymptotic case, when the degree l of a pulsation mode is much smaller than the order (overtone) of this pulsation n. Tassoult (1980) has derived an asymptotic solution for p-modes:

$$\nu_{n,\ell} = \Delta\nu_0 \cdot \{n + \frac{\ell}{2} + \epsilon - \delta_{n,\ell}\}$$

with $\delta_{n,\ell} = \frac{\ell(\ell+1)\alpha+\beta}{n+\frac{\ell}{2}+\epsilon}$, and

$$\Delta\nu_0 = \{2\int_0^R \frac{dr}{c}\}^{-1}.$$

The polytropic index of the model is 2ε, whereas α and β are constants depending on the internal structure of the star, and c is the travel speed of sound.

For a rotating star, the unperturbed frequency $\nu_{n,l}$, as observed from the earth, is further split in a symmetric frequency multiplet according to:

$$\nu^{rot}_{m,n,\ell} = m \cdot (1 - C_{\ell,n}) \cdot \Omega,$$

with $-l<m<l$, m being an integer, Ω the stellar rotation frequency, and C a constant which strongly depends on the stellar structure.

In addition, the global magnetic field structure of a star also influences the eigenfrequencies and pulsation amplitudes. Hence, amplitude ratios of frequency multiplets allow to derive information on this magnetic field structure.

As is evident, a full mode identification (n, l and m) is necessary in order to compare any observed pulsation frequency with predictions. For most of the classical pulsating stars only one pulsation frequency has been observed, sometimes two, very rarely three frequencies. Frequently, the observed frequencies do only poorly correspond to those predicted by models. The solution to this discrepancy is often prevented by an unknown full mode identification.

Asteroseismology – a New Tool

In asteroseismology the analysis of the stellar structure will not be based on the observation of one or two frequencies, but on a frequency spectrum which allows the determination of characteristic periodic structures within such a spectrum. No individual mode identification is necessary in this case.

The kind of results we can expect for distant stars are illustrated by the full disk solar power spectrum obtained by the Iphir experiment on board the Phobos probe towards Mars (Fig. 4). In this power spectrum of the Sun – seen as a star –, we can distinguish up to 30 low-degree modes. Two quantities can be measured to a very high accuracy in such a power spectrum: the "large" and the "small" separations. The large separation $\Delta\nu_0$ is the frequency difference between two modes of same degree l, but of quantum numbers n differing by one. The small separation δ_{nl} is the frequency difference between mode n, l and mode n−1, l+2. It turns out that $\Delta\nu_0$ depends on the "average" sound speed in the stellar interior, and therefore carries information on the "average" structure, while δ_{nl} is sensitive to the details of the stellar structure close to the core.

Once the large and the small separations have been measured to a high accuracy for a given star, one can, for example, locate them in the so-called asteroseismological HR diagram, where the structure constant D_0, proportional to the small separation, is plotted versus the large separation $\Delta\nu_0$. This diagram was introduced into asteroseismology by J. Christensen-Dalsgaard (Aarhus). In such a diagram (Fig. 5), lines of constant mass (full lines) and lines of constant central hydrogen content (dashed lines) can be drawn. The central hydrogen content is an excellent age indicator. By placing the measured large and small separations in the asteroseismological HR diagram, one can derive with a good accuracy the mass and age of a star.

Further diagnostics is provided in an 'echelle' diagram (Fig. 6) in which the frequencies are plotted modulo $\Delta\nu_0$. The curvature of the lines appearing in an echelle diagram (one line for each value of l) is very sensitive to the details of the structure just below the stellar surface. Thus, low-degree modes can also be used to probe these regions.

Finally, and as was already mentioned, a further dependence of the frequencies on the azimuthal order m is introduced when a star rotates, known as the rotational splitting. This splitting depends on the integral of the internal

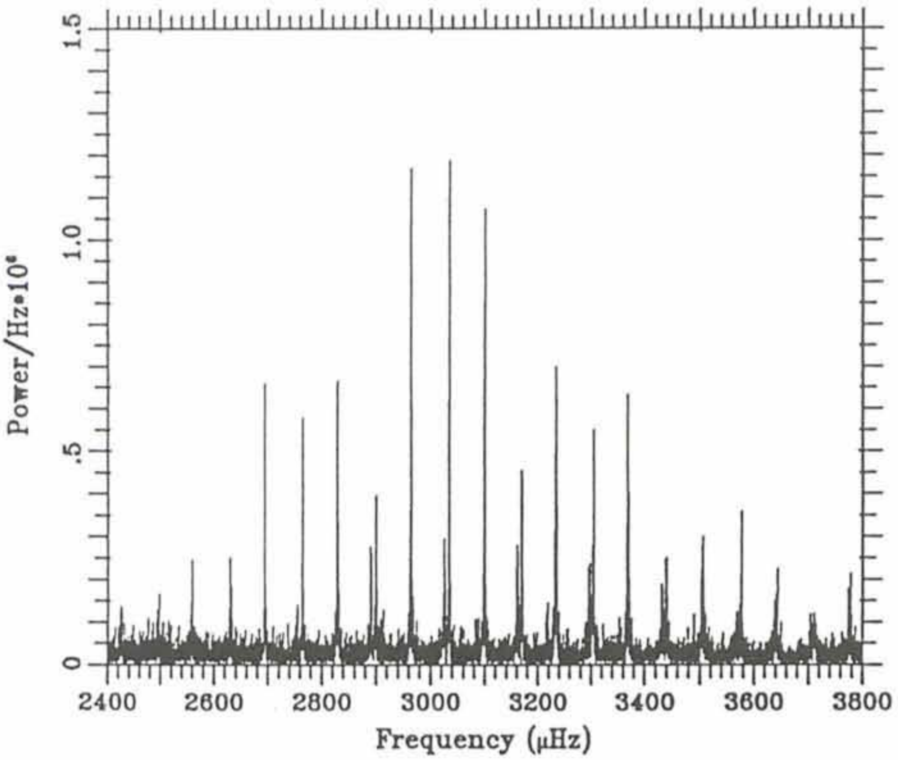

Figure 4: *Power spectrum of the low-degree p-modes from 160 days of the IPHIR experiment.*

rotation over the region crossed by the mode under consideration (i.e. for most of the stars the low-degree modes), and hence can provide an estimate of the internal rotation.

Seismological techniques have been applied extensively to the Sun, and helioseismology has brought an enormous amount of information about the solar interior. Among other results, it was shown that solar p-mode frequencies are not compatible with presently assumed core mixing, with the existence of Weakly Interacting Massive Particles (WIMPS), that there is no fast spinning core in the Sun, and that solar internal rotation is not constant on cylinders, as suggested by some theories.

For other solar-type stars on the contrary, only very few results have been obtained so far. In fact, only marginal detection of pulsation has been claimed for two very bright slow rotators (Gelly, Grec, Fossat: 1986, *Astron. Astrophys.* **164**, 383): α CMi (Procyon) and α Cen (Rigil Kent). In the respective power spectra for the radial velocity variations, no clear evidence for $\Delta\nu_o$ and δ_{nl} emerge and therefore no reliable information can be extracted about the internal structure of these two stars.

This lack of clear asteroseismological results is caused by the extremely low signal that must be detected in the case of, e.g., solar-type stars. Two observable quantities can be used for asteroseismology:

- Brightness fluctuations induced by the pulsations: These fluctuations amount to only 10^{-6} mag. for typical solar-type stars. As will be shown later, photometric measurements down to this accuracy are not possible from the ground.
- Velocity fluctuations induced by the pulsations: These are of the order of 10 cm s^{-1} for solar-type stars, and this type of measurements represent an important technological challenge, not totally out of scope, though. However, these measurements are limited to only a few very bright objects, because of the high spectral resolution and the high S/N ratio required. They are also limited to very slow rotators, because sharp spectral lines are needed to reach the desired accuracy. Unfortunately, slow rotators are not the most interesting objects to study (no measurable rotational splitting, not efficient dynamo), and therefore the first class of methods should be preferred for a systematic study.

Although we are concentrating here on 'normal' stars, it has to be mentioned that more exotic objects, like white dwarfs and nuclei of planetary nebulae, have benefitted enormously from asteroseismology.

In conclusion we can say that asteroseismology is a powerful tool to probe the internal structure and dynamics of stars, and therefore to contribute to the solution of the current basic problems of stellar physics by providing two independent observables ($\Delta\nu_o$ and δ_{nl}). However, as current stellar evolution theories characterize a star by five independent parameters (mass, initial mass fraction of Helium (Y) and metals (Z), age and mixing length), additional data have to be provided for a full test of stellar interior and evolution models. Hitherto, in most cases only the effective temperature and luminosity can be measured, accounting for two further independent parameters, out of the total of five needed.

Scientific Impact of Asteroseismology

In the following sections we will try to highlight the most prominent aspects of stellar physics which will benefit – and have already benefitted – from asteroseismological projects.

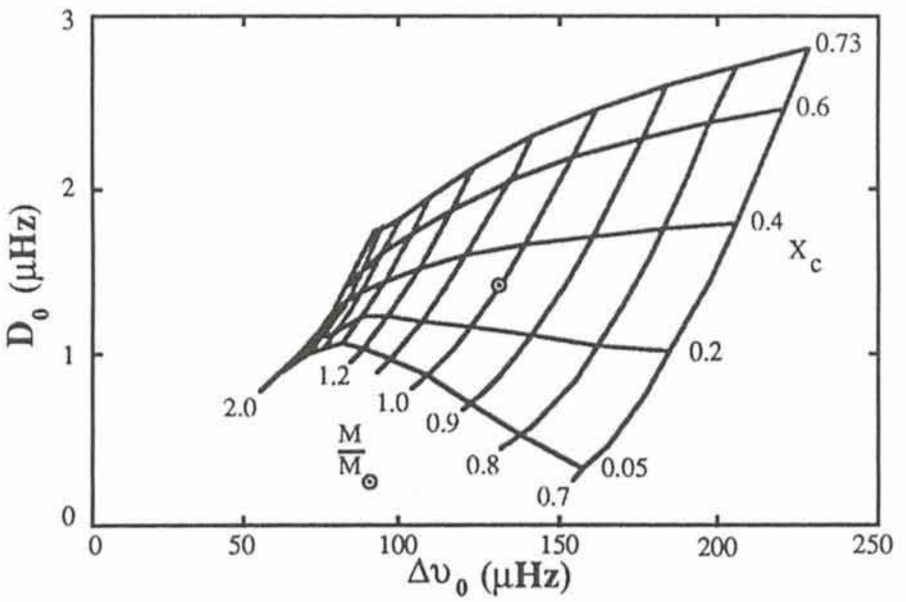

Figure 5: *The asteroseismological HR Diagram.*

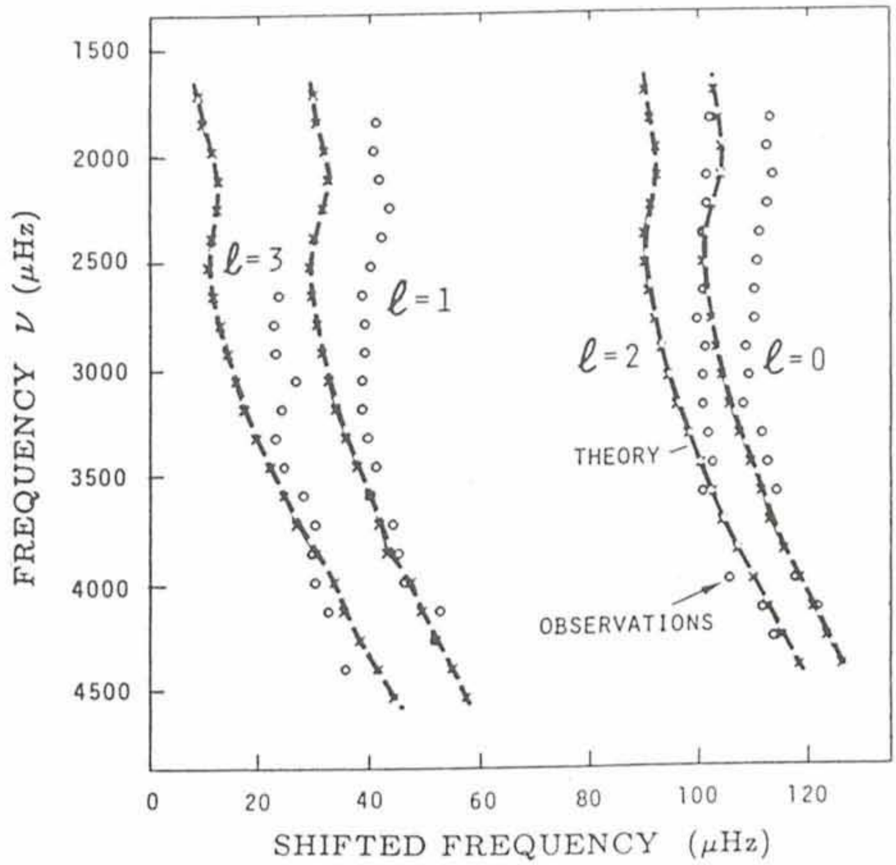

Figure 6: *Echelle-diagram for the solar p-mode oscillations.*

- *Stellar interior:* For individual stars, as mentioned above, we usually have 2 observables: the absolute luminosity, which can now be known to a high accuracy thanks to the Hipparcos satellite, and the surface gravity, known to a much lower accuracy. The mode frequencies provided by the asteroseismological data will yield additional observables to test stellar models. In particular, the large and the small separations will be measured to a very high accuracy. These two observables are directly sensitive to the details of internal structure, while the usual observables are surface properties of the stars and are only indirectly sensitive to the internal structure.
- *Stellar evolution:* With the availability of very precise frequency measurements it will be possible to detect stellar evolution effects even within an active life time of a scientist. This has been investigated, among others, for white dwarfs by D. Winget, for roAp stars by St. Kawaler, and for δ Scuti stars by M. Breger.
- *Excitation and convection:* Convection is thought to be responsible for mode excitation in solar-type stars. Therefore, measuring mode amplitudes and life-times of stars of different types and ages will have a very important impact on the theories of mode excitation, and as a consequence on our understanding of stellar convection.
- *Angular momentum distribution and transport:* The problem of angular momentum is among the most important in stellar physics. The issue is to understand how stars get rid of their initial angular momentum, how angular momentum is distributed and is transported in stellar interiors during a star's life. Providing an estimate of internal rotation through rotational splittings and a measurement of surface rotation through observed rotational modulation of white light as well as of UV lines will give a hint about angular momentum distribution within stars. The differences seen between stars of different ages will tell us how angular momentum is transported during stellar evolution.
- *Dynamo theories:* The mode frequencies and the separations provide an estimate of stellar ages and masses. The frequencies and separations, with the addition of mode amplitudes and life-times, will result in constraints on the structure of convective zones. Moreover, as indicated previously, the simultaneous estimates of internal rotation (rotational splittings) and of surface rotation (rotational modulation) will provide an estimate of the angular velocity gradient, and a hint on the rotational shear at the base of the convection zone.

Asteroseismology at La Silla

Already since the early stages of asteroseismology ESO has granted telescope time to various projects in this field. In the following we can only give a very brief summary which will be biased towards our own activity and is based mainly on after-dinner 'shop talks' at La Silla. We apologize for being ignorant of other important projects.

One group of stars which contributed to the boom in asteroseismology is the group of pulsating magnetic CP2 stars, also called, but less precisely, rapidly oscillating Ap (roAp) stars. Soon after the discovery of the first member of this group with periods of about 10 minutes by Don Kurtz (South Africa) in 1979, confirming observations were gathered at La Silla with the 50-cm Danish telescope in Strömgren and Hβ colours. The full story is already told in *The Messenger*, No. **33**.

In the beginning of the eighties, some surveys had already been initiated to check CP2 stars for stability against δ Scuti type pulsation with few hours period. Our survey at La Silla, e.g., is still ongoing and uses mainly small telescopes (50-cm telescopes, 0.9-m Dutch telescope and the 1-m ESO telescope). The recently descoped Walraven photometer proved to be particularly useful, because it allowed to obtain simultaneous 5-colour data. The potential of multicolour information on mode identification is illustrated in *The Messenger*, No. **34**, p. 9. Furthermore, Matthews, Wehlau and Walker (*Astrophys. J. Lett.*, **365**, L81) have shown that such observations, supplemented by data from the IR, allow to derive the atmospheric temperature stratification. The first observations of roAp stars in the near IR have also been obtained at La Silla.

La Silla usually plays an important role in observing campaigns organized to obtain long and uninterrupted data sets which are not affected by the day-night cycle. Several such campaigns have already been successful for various δ Scuti (e.g. M. Breger with Bochum observers) and roAp stars.

The observations of solar-type oscillations of Procyon and α Cen, mentioned earlier in this article, have been obtained by the Nice group primarily at La Silla. Other very important activities in asteroseismology are currently ongoing at the Danish 1.5-m telescope, where S. Frandsen (Aarhus) and his colleagues investigate various clusters of different age for δ Scuti stars. The Geneva group has accumulated and published a lot of data related to microvariability, δ Scuti, β Cephei and RR Lyr variables. Similar holds true for the Leiden group, using the famous Walraven photometer. Very probably, this list of photometric and spectroscopic projects carried out at La Silla is incomplete, but yet suited to illustrate the significance of the excellent ESO site for asteroseismology, as well as for the importance and effectivity of small and medium sized telescopes. "Big Science" not always demands "Big Telescopes".

Finally, we would like to briefely touch on our future projects at La Silla related to asteroseismology, in addition to continuing our survey and participating in world-wide observing campaigns.

As has been clearly demonstrated by a recent ESA Assessment Study for project PRISMA (*ESA SCI* (**91**) 5, asteroseismology will enter a new era, if observations can be done from space. The elimination of atmospheric noise and the possibilities of very long, continuous data strings with a large duty cycle are the main reasons. One such asteroseismological space experiment is already approved for the Sovjet MARS-94 probe and has the acronym EVRIS. The other space project, more versatile, elaborate and powerful, is presently in Phase A study at ESA and is called PRISMA (Probing Rotation and Interior of Stars: Microvariability and Activity).

As already shown earlier in this article, supplementing ground-based observations are mandatory for a full exploitation of the scientific potential of asteroseismology. In the case of EVRIS, basic stellar data of sufficient accuracy, like effective temperature, log g and luminosity are missing for many EVRIS target stars. Furthermore, a careful investigation of the immediate vicinity of the very bright target stars is necessary in order to avoid a poor target choice. Photometric problems may arise from even very faint background sources which drift in and out of the photometer aperture due to satellite jitter. To our surprise, there are presently no data archives available which would allow to extract the required astrometric and photometric information for EVRIS. As a consequence, all the candidate target fields have to be carefully observed in various colours with CCD techniques.

This synergy between space- and ground-based observations is another example for the necessity to develop both and not to ignore one at the expenses of the other.

Words of thanks: Many colleagues, impossible to list all here, have contributed to this article through discussions, cooperations and contributions. WWW is particularly grateful to the teams of EVRIS and PRISMA.

Multi-Wavelength Observations of Infrared-Bright Carbon Stars

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1. Introduction

The carbon star phase is one of the last phases of evolution of intermediate mass stars (1-8 solar masses). Carbon stars reside on the Asymptotic Giant Branch (AGB) in the Hertzsprung-Russell diagram. The carbon is produced in thermal pulses, short periods of explosive He-shell burning, and transported to the surface by convective mixing. Many of the physical processes that play a role in the formation and evolution of carbon stars are still poorly understood, e.g. the production and dredge-up of carbon, the origin and evolution of the mass loss. Here we briefly report on an observational study of infrared-bright carbon stars.

In a recent paper Groenewegen et al. (1991) have studied an infrared-complete sample of bright carbon stars containing all 109 carbon stars with $S_{12}>100$ Jy in the IRAS PSC. This sample is more complete than others previously studied in that both optical and infrared carbon stars are included.

Using near-infrared photometry from the literature they derived near-infrared colour temperatures and from the energy distribution they calculated infrared bolometric corrections. Distances were derived assuming $M_{bol}=-4.9$, corresponding to $L=7050\ L_{\odot}$. From available CO data mass-loss rates were calculated for about 80 stars in their sample.

The sample was divided into five groups depending on their infrared properties, extending the classification of carbon stars of Willems and de Jong (1988). Group I stars show the silicate feature in their LRS spectra, possibly because they are very recently formed carbon stars. Since none of the known Group I stars is bright enough to have made it into the sample they will not be dicussed further. Group II stars have a pronounced 60-μm excess, high near-infrared temperatures, small bolometric correction and low mass-loss rates. They probably turned into a carbon star quite recently and their excess at 60-μm is due to a cool circumstellar shell, probably the oxygen-rich remnant of the preceding high mass loss phase. From group III to V the mass-loss rate of carbon stars steadily increases, and as a consequence the near-infrared temperatures decrease and the bolometric corrections increase.

Using average bolometric corrections for each group the infrared-complete sample was transformed into a volume-complete one. The scale height of carbon stars is found to be 190 pc and their local space density equals 185 kpc^{-3}.

From the calculated space densities of carbon stars in each group relative timescales are derived. Adopting a lifetime of 20,000 years for group II stars from model calculations, Groenewegen et al. find a total lifetime of the carbon star phase of about 26,000 years, uncertain to a factor 2. The total mass lost during the carbon star phase equals about 0.04 $M_{\odot}$. This number is uncertain to a factor 5, a factor 2 arising from the uncertainty in the lifetime of group II stars and a factor 2.5 arising from the uncertainty in the mass-loss rates. For an adopted average white dwarf mass of 0.65 $M_{\odot}$ this implies that most stars are already of low mass when they turn into carbon stars, probably around $0.69_{\odot}$ and certainly less than 0.85 $M_{\odot}$.

The location of the 109 stars in the IRAS colour-colour diagram is shown in Figure 1. The colours $C_{21}=2.5\log(S_{25}/S_{12})$ and $C_{32}=2.5\log(S_{60}/S_{25})$ are indicated along the axes. As discussed