

PROJECT COMPLETION REPORT

IFCPAR PROJECT NO. 25-2504-32

DYNAMICS OF SOLAR AND STELLAR INTERIORS: SEISMOLOGY AND ACTIVITY
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SUMMARY

The project aims to contribute to the improvement of our knowledge of stars. By combining the efforts of the French and Indian teams an attempt has been made to improve our understanding of solar and stellar structure, and to identify the physical mechanisms responsible for their activity. Models were developed for solar irradiance and the role of various key parameters in understanding solar variability was identified. Using data provided by helioseismology and asteroseismology from ground and space permitted us to probe the solar interior with a high precision, thus enabling us to build solar models of comparable accuracy. It was also shown that gravity modes can be used to detect the internal magnetic field in slowly pulsating B stars. A major outcome to emerge naturally from the project is a proposal between the Indian Institute of Astrophysics, Bangalore, India and French astronomers from the Paris Observatory and Midi-Pyrenees Observatory, Toulouse for a high resolution spectrograph and spectropolarimeter for the 2-m Chandra telescope at Hanle in the Leh Ladakh region.

1. Solar Interior: Mixing and angular momentum transport

The tachocline is a region of high shear, where the rotation rate changes abruptly from differential in the convection zone to almost uniform beneath in the radiative, stably stratified interior. The presence of this region has an effect on the overall structure of solar-type stars, and the mixing which occurs there is at least partly responsible for the lithium depletion observed in such stars. Moreover, the tachocline is believed to play a crucial role in the dynamo mechanism, by shearing the poloidal magnetic field into toroidal field. Applying a parametric prescription for the turbulent mixing and angular momentum transport within the tachocline, an improved model of the Sun, (using the CESAM code developed by the French collaborators) was built. The seismic properties of this model (calculated by the Indian collaborators) comply with the constraints of acoustic sounding.

In particular, constraints were put on the nuclear reaction cross-section for the proton-proton, $\text{He}^3\text{-He}^3$ and $\text{He}^3\text{-He}^4$ nuclear reactions and microscopic diffusion coefficients. The inferred photospheric hydrogen abundance is found to be 0.732 ± 0.001 by mass. The nuclear reaction cross-section for the fundamental proton-proton reaction is found to be $S_{11}=(4.06 \pm 0.07)$

10^{-25} MeV barns, which is 1.5% higher than the present theoretical estimates. The incorporation of macroscopic mixing in the tachocline region removes the well-known discrepancy in the sound speed of solar model near the base of the convection zone. The sound speed in these improved solar models is within 0.1% of that in the Sun as inferred from seismic inversions.

This model confirmed that the observed deficit of solar neutrinos could not be explained by some shortcomings of the solar model, but that it had to be ascribed to non-standard property of the neutrino.

2. Asteroseismology

Seismic signature of convective cores in intermediate mass stars

The seismic signature of convective cores in stars in the mass range 1.2 to 2.0 solar masses was studied. Intermediate degree modes of the solar oscillations have previously been used to determine the solar helium abundance to a high degree of precision. However, we cannot expect to observe such modes in other stars. In this work an investigation was made on whether low degree modes that should be available from space-based asteroseismology missions can be used to determine the helium abundance, Y , in stellar envelopes with sufficient precision. It was found that the oscillatory signal in the frequencies caused by the depression in the second helium ionization zone can be used to determine the envelope helium abundance of low mass main sequence stars. For frequency errors of 1 part in 10^4 , we expect errors σ_Y in the estimated helium abundance to range from 0.03 for 0.8 solar mass stars to 0.01 for 1.2 solar mass stars. The task is more complicated in evolved stars, such as sub-giants, but is still feasible if the relative errors in the frequencies are less than 10^{-4} .

Asteroseismic diagram for low degree modes

An asteroseismic diagram was constructed using low degree ($l=0,1$) acoustic or p-modes. This is similar to, but different from the classical Christensen-Dalsgaard diagram involving the $l=0,2$ modes. It was demonstrated that the local 5-point small separation between $l=0,1$ modes is a smoother diagnostic than the classical 3-point separation. The asteroseismic diagram plots the mean value of these 5-point small separations averaged over a frequency range versus a similar average of the large separations. A relationship between the small separations and the internal phase shift of the oscillation eigen-solutions is shown. Except in the asymptotic limit of high frequencies, the separations between $l=0,1$ and $l=0,2$ modes encode different information on the stellar interior and therefore provide different diagnostics of stellar evolution.

3. Magnetic fields & Activity

Behavior of magnetic tubes in the photosphere of solar-like stars

An important physical quantity basic to the understanding of stellar magnetism is the field strength in small-scale flux tubes and spots on the photosphere. Measurements and interpretation of magnetic field strengths in cool main sequence stars other than the Sun have been subject of much debate because of the difficulties associated with the modelling of the atmospheric structural changes that the inhomogeneous fibril state of the magnetic field strengths. The observed Zeeman broadening on cool stars is believed to be produced by small flux tubes that appear bright, similar to the solar magnetic network and facular bright points, rather than by spots.

It is widely believed that the mechanism responsible for generating intense fields in small-scale flux tubes is convective collapse. This mechanism is investigated for solar like stars using realistic atmospheric models of the super-adiabatic upper convective zone layers of such stars. The strengths of convective stable flux tubes were computed as a function of surface gravity and effective temperature. Stars with $T_{\text{eff}} \geq 5500$ K and $\log g \geq 4.0$ show efficient collapse and hence strong field strengths close to thermal equipartition limits, even in cool stars, implying highly evacuated tubes, for which possible reasons are suggested.

Solar irradiance

Studies were carried out of the precise measurements of total solar irradiance (TSI), which reveal a remarkable inconstant Sun whose brightness varies in phase with the solar activity cycle over time scales from minutes to years and decades. The short-term changes of irradiance are

primary caused by the passage and evolution of sunspots and faculae across the visible disk. The detailed analysis of sunspot and facular areas clearly shows a quadratic relationship between these quantities and implies that the facular areas have greater influence on TSI near the solar maximum. Regression models of TSI composite time series have been developed to study the temporal variation in TSI for different time epochs using photometric indices from San Fernando Observatory. The proxies for these indices have also been used to regress TSI on short- and long-time scales. The models calculated using proxy indices on shorter time scale (less than a month) show poor correlation while on longer time scale, the correlation is highly significant. The 10.7 cm radio-flux and sunspot number have been used to estimate the change in total irradiance in past solar cycles.

In this recent work, the hypothesis that the solar irradiance variability is mainly influenced by the changes in the solar surface magnetic fields was examined. Models based on the magnetic field indices derived from synoptic magnetograms of Mt. Wilson Observatory, i.e. Magnetic Plage Strength Index (MPS) and Mt. Wilson Sunspot Index (MWSI), were used to study the effects of surface magnetism on the total solar irradiance variability during solar cycles 21, 22 and 23. It was found that most of the solar cycle variation can be accounted for by the absolute magnetic field strength on the solar disk, if fields associated with dark and bright regions are considered separately. However, there is a large scatter in the calculated and observed values of the TSI during solar cycle 21. This difference may be attributed to the dubious/overestimated values of MPSI used in the analysis. On the other hand, multiple correlation coefficients obtained for solar cycles 22 and 23 are 0.88 and 0.91 respectively. Furthermore, separate regression analyses for solar cycles 22 and 23 do not show any significant differences in the total solar irradiance during these cycles. Thus, these findings clearly demonstrate that the surface magnetism plays a crucial role in modulating the solar solar irradiance and no additional factor is required to explain the inter-cycle trends in the irradiance variability.

Probing the internal magnetic field of slowly pulsating B stars through g modes

Extensive observation campaigns have uncovered the existence of a class of variable stars known as slowly pulsating B (SPB) stars, which are multiperiodic typically over a time scale of days. These pulsations have been identified with low degree (typically $l=1$ and 2) g modes of high order, that are excited by the κ mechanism in the metal opacity bump at a temperature of about 2×10^5 K. These modes often occur in multiplets with closely spaced periods (with a typical separation of 1%). In some cases this separation can clearly not be due to rotational splitting, which would yield much larger spacings. In this work it is proposed that such frequency splittings are due to the presence of a magnetic field. If this hypothesis is correct, then the splitting of frequencies can be used to estimate the field strength in the interior of SPB stars.

It is well known that a magnetic field modifies the elastic properties of a star. In particular, it splits the oscillation eigen-frequencies into several components, and therefore from the observed splitting it is possible, in principle, to deduce the strength of the magnetic field. So far the attention has focused on acoustic modes, but the effect of the magnetic field is likely to be more pronounced for internal gravity modes, because they are of lower frequency. Certain stars, such as SPBs are pulsating in such modes, and they thus appear as an excellent target to determine the strength of the magnetic field inside massive stars, which until now has been open only to speculation. Some data are already available by observing these stars from the ground, but soon much more frequencies should be detected through asteroseismology from space.

The idea is based on earlier work by Hasan and Christensen-Dalsgaard (1992, *Astrophysical J.* **396**, p. 311) which analytically investigated the effect of a vertical magnetic field on p and g modes in a plane-parallel isothermal stratified atmosphere. It was found that even a weak field can significantly shift the g -mode frequencies --- the effect increases with mode order. In the present study the classical perturbative approach is used to estimate the internal field of a 4 solar mass SPB star by looking at its effect on a low-degree ($l=1$) and high-order ($n=20$) g mode with a period of about 1.5 day. It is found that a polar field strength of about 110 kilogauss (kG)

on the edge of the convective core is required to produce a frequency shift of 1%. Frequency splittings of that order have been observed in several SPB variables, in some cases clearly too small to be ascribed to rotation. It is suggested that they may be due to a poloidal field with a strength of order 100 kG, buried in the deep interior of the star.

4. Ground based observational networks: Hanle echelle spectropolarimeter (HESP)

Considerable effort went into examine common ground-based observation campaigns between the French and Indian astronomers, and also to build appropriate instrumentation for this purpose. A project of developing in India a new generation spectrometer and spectro-polarimeter, analogous to ESPADONs, installed on the Canadian-French telescope at Hawaii and Pic du Midi, France was initiated in October 2002 during S.S. Hasan's visit to Paris, Toulouse and Pic du Midi, and followed up during Hasan's visit to Paris and Toulouse in October 2003 and C Catala's visit to IIA, Bangalore in October 2003.

A working group of astronomers was formed at IIA to examine this project and has prepared a concept report on the scientific objectives and broad technical aspects of the proposed instrument, called the Hanle Echelle Spectro-Polarimeter (HESP) for installation on the 2-m Chandra telescope at Hanle in the Himalayas. HESP should be capable of high resolution spectroscopy in order to:

- (a) study chemical abundance, search for extra-solar planets,
- (b) examine mass loss in evolved stars,
- (c) carry out Doppler imaging of spotted stars, and
- (d) search for binary companions in different families of stars.

Furthermore, it will also have a spectro-polarimeter with which it will be possible to:

- (a) study starspots and activity,
- (b) carry out polarimetric studies of the Hanle effect in spectral lines,
- (c) examine strong magnetic fields in magnetically active stars and RS Cvn stars. and
- (d) study the geometry and chemistry of circumstellar scattering matter.

In order to successfully carry out the scientific programmes mentioned above, the instrument must have the following technical requirements:

- (a) resolving power of at least 50,0000,
- (b) large continuum spectral coverage from 370 to 900 nm,
- (c) possibility of recording two interleaved spectra,
- (d) highest possible throughput of about 20% to study 11-12 magnitude objects.

The optical configuration of the spectrograph will be similar to ESPADONS which is inspired by FEROS, a well-know bench mounted fiber-fed spectrograph presently being used at the European Southern Observatory's 1.52-m telescope along with a polarimeter.

Such a state of the art instrument installed at two sites (Hawaii and Hanle, India), well separated in longitude, will constitute the first step of a worldwide network. It will allow co-ordinated observations with a large duty cycle, well suited to study precisely time dependant phenomena (oscillations, activity) on different time scales. The development of this instrument is being done in scientific and technical collaboration with French scientists and engineers working at Meudon and Toulouse.

The basic strategy for development is that a company in Europe will undertake the fabrication of the instrument, based on technical drawings and design information provided by the French scientists. Scientists and engineers of IIA would, however, be involved at all stages of the fabrication. Such a company has been identified and a memorandum of understanding will shortly be worked out. The new instrument is likely to be commissioned in about three years.

The development of a detailed proposal for a spectropolarimeter for the 2-m telescope at Hanle in the Himalayas is a major outcome of the Indo-French collaborative programme. This proposal has been positively received by the Department of Science & Technology, Government of India and is likely to be fully funded by them.

5. Preparation for the COROT mission

Several important aspects were addressed concerning the preparation of the Corot Mission. An important step was taken which overcame some of the earlier outstanding problems with CESAM (the French stellar evolution code) that is used to extract information about stellar interiors from typical seismic data sets to be expected from the COROT asteroseismic mission. After some effort it was possible to overcome some of the earlier outstanding problems in the code and successfully interface it with the Bombay (Antia) code.

A. Mazumdar, E. Michel, M-J. Goupil and J. Lochard participated in the COROT Hare and Hounds activities. The aim is to examine the feasibility of extracting information about stellar interiors from typical seismic data sets to be expected from the COROT asteroseismic mission. In this blind exercise, one group of scientists produce a model of a potential primary target star and obtain the theoretical frequencies of its low degree oscillation modes, based on a few global characteristics of the star measured from the ground. In subsequent steps, different groups of scientists carry out the tasks of generating a synthetic time series, extracting frequencies and seismic analysis of the frequencies without any prior knowledge of the actual original input model. The final objective is to infer about the internal structure and rotation of the star, based on its oscillation frequencies which have been processed through the entire pipeline of data analysis, as might be expected for a real star observed through the COROT telescope. This exercise also helps in the final choice of the target stars from several potential candidates.

They have carried out a seismic analysis of two among the four such stars selected for the hare and hound exercise. Their analysis consists of three levels. At the first level, we constrain the range of the input parameters of the stellar model by constructing evolutionary tracks and comparing them with the supplied luminosity and effective temperature of the star. At the next level, they aim to obtain a stellar model, which is very close to the original unknown model. Exploiting the various characteristics of the large and small frequency separations of stars achieve this. They have devised a method to systematically search for the closest model in the space of the model parameters, using the frequency separations as the criteria for comparison. At the final level, they attempt to probe the stellar interior by applying inversion techniques (described below) using the closest model obtained at the previous step as the reference model.

As a contribution to the preparation of the COROT mission, S.S. Hasan and J.P. Zahn undertook a project to evaluate the magnetic splitting in SPB stars, and to assess the feasibility of determining the interior magnetic field. It should lead to a selection of the best targets of this type for the programme of observation of COROT. Several important aspects have already been addressed concerning the preparation of the COROT Mission, as described in previous sections.

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