Probing the internal structure of stars

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One generally sees only the light which escapes from the outer layers of a star, so the study of the internal structure of such objects has been a purely theoretical subject for many decades. Nowadays, the development of a very efficient discipline called "helioseismology", more generally "asteroseismology", gives us a real view through the Sun and contributes to the revelation, as, in the case of the Earth, of the internal properties of the stellar plasma. One of the major objectives of the satellite SOHO, launched five years ago, is to make progress on the physical mechanisms that describe the solar interior. In pursuit of this aim, three experiments: GOLF, MDI and VIRGO, look continuously at the persistent seismic movements of the solar surface due to the presence of acoustic waves. They use different methods: GOLF and MDI measure the time variability of the Doppler velocity, VIRGO measures the variability of the luminosity. Comparing different techniques contributes to understanding properly all the biases which may pollute the results and gives more and more confidence in our ability to check the internal properties of stars.

The stability of the stars is due to the competition between gravitational forces and radiation pressure but these processes cannot explain the great longevity of the stars. In 1920, Eddington was the first to imagine that the life of stars is dominated by the central nuclear fusion, in producing a nuclear energy which compensates for the energy lost at the surface. The first stage is the hydrogen burning, it is also the longest one, lasting from several million to billion years (about 10 billion years for the Sun). The Sun is more or less at the middle of this stage, producing helium in its nuclear core. This stage is followed by helium burning producing carbon and oxygen, then in some stars followed by carbon burning producing neon, sodium, magnesium, aluminium and silicon, then silicon burning and for the most massive stars iron burning and supernova explosions... Most of the elements we know on the Earth are synthesized in the core of the stars. The understanding of this sequence has been a great discovery of the first part of the 20th century and has allowed us to build up the main features of stellar evolution and one can estimate today for each star of the sky an age as far as we know its luminosity and surface temperature.

Since this epoch, and owing to the development of nuclear physics and atomic physics, one has been able to solve the structural equations which govern the hydrostatic equilibrium, the conservation of mass and the production and transport of energy of any star by introducing fundamental physics such as nuclear reaction rates, the equation of state and photon-matter cross sections for all the different thermodynamical conditions one may find in a star. This theoretical effort supposes that one can define precisely the properties of the plasma from the central region where most of the species are totally ionized up to the surface where molecules begin to appear. Stars evolve in space and time and only large computers may follow such evolution in detail.

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To check all these assumptions, astrophysicists have observed a very large number of stars which are representative of all the different steps of evolution. Among them, the Sun represents by itself a unique case for which two kinds of probes are accessible.

The detection of solar neutrinos produced by specific nuclear reactions is a unique tool. The main advantage of this probe is the extreme sensitivity of some neutrino fluxes to the central conditions of the Sun: some reaction rates enhance by a factor of 18 an uncertainty in the temperature (an error of 1% in solar central temperature leads to an error of 18-20% on the emitted flux of neutrinos associated with the decay of ^8B). But the main difficulty is the extremely small interaction cross section of the neutrinos with matter (10^{-46} to 10^{-40} cm²) and consequently with the detector. During the last two decades that one has succeeded to measure neutrinos in different detectors (initially the chlorine interaction with a factor of 3-4 deficit), the neutrinos detected represent only 30% to 60% of the theoretical values of emitted neutrinos depending on the range of energy considered.

In parallel, in the years 1980-90, helioseismic measurements have put some constraints on the external layers of the Sun. The solar sound speed profile has shown significant disagreement with the profile obtained with a model using the simple assumptions of stellar evolution (fig. 1a). These measurements have first contributed to improving our representation of the stars in precisely determining two quantities: the localized transition between radiation and convection and the photospheric helium. These results have shown that one physical process was missing in the calculation: the migration of the elements with time from the surface to the interior. Adding this process has led to improved agreement between the theoretical estimate of the solar interior and the seismic observation, which agree now along the solar radius to within 1% (comparison of fig. 1a and fig. 1b red line). But in doing so, the neutrino predicted fluxes were not in better agreement with the observations, and even a little worse.

So a lot of questions have been addressed to the different communities (astrophysics, nuclear physics, particle physics, plasma physics):

- Are the solar neutrino experiments accurate enough? Could the long integration time (several years) partly hide the instantaneous information? Nowadays the SuperKamiokande experiment in Japan, a real time experiment, has measured about 4500 solar neutrinos per year since 1996, for which the directivity and energy is determined and there is no longer a problem of statistics. The discrepancy is always present.

- A second series of questions is directly addressed to the neutrino itself and the possibility that beyond the particle standard model, this particle has a mass. The atmospheric neutrino experiments, in detecting ν_{mu} , already suggest that these neutrinos are probably massive and may oscillate with ν_{e} neutrinos. Could the Sun reveal some electron neutrino properties not presently accessible in the laboratory? The Canadian experiment SNO, which began operating in 1999, will be able to partly check this point by measuring the different flavours of the neutrinos, thanks to the use of heavy water.

In the two cases previously mentioned, only high energy neutrinos corresponding to the production of boron are measured, which are not the easiest to predict. In the future, improvements in the statistics of the gallium experiments will check the answer and variability of these radiochemical experiments. They are very interesting as they detect low energy neutrinos, in particular those emitted by the interaction between protons which are directly connected to the nuclear energy production. And very soon, other checks will be accessible with the Borexino experiment which is dedicated to neutrinos produced by the electronic capture on ^7Be .

Finally, physicists are seeking to find a good way to measure the whole neutrino energy spectrum produced by the reaction rates inside the Sun. This is very important to have a precise vision of the different sources of neutrinos and not an integrated value.

But there is a last series of questions addressed to our knowledge of the solar interior. How do we check the whole calculation of stellar evolution in its details? Are we so sure of the properties

Fig. 1: Relative difference between the squared sound speed in the Sun extracted from helioseismic measurements and the squared sound speed of the Saclay reference solar model. Fig. 1a: In the nineties, the difference was still large and the nuclear region was badly known. A lot of processes had been invoked to explain the discrepancy between predicted and detected neutrinos such as large mass loss in young Sun, WIMPS and turbulent mixing. Models including such processes are shown and disagree with the observed sound speed (Turck-Chièze et al., Phys. Rep. 1993).

Fig. 1b: the measurements are from GOLF + MDI (Rhodes et al., 1997, Sol. Phys., Bertello et al.

ApJ. 1999 and ApJ.lett 2000, García et al. Sol. Phys. 2001). The main improvements of the model (red curve) are the inclusion of microscopic diffusion and fundamental physics (opacities, equation of state, nuclear cross sections). The peak at the base of the convective zone in red curve located at $0.71 R_{\odot}$ (solar radius) or $0.98 M_{\odot}$ (solar mass) illustrates a region of turbulence. The blue curve corresponds to a model where we add a turbulent term to simulate an hydrodynamical instability at the transition radiation-convection. Finally the black curve, which contains also the error bars of the observations, corresponds to a seismic model where the physical ingredients, namely the pp reaction rate, metallic content and radius, have been adjusted in their known uncertainties to reproduce the Sun seen by acoustic modes (Turck-Chièze et al. ApJ lett 2001).

of the nuclear interaction in a stellar plasma which is not accessible to the laboratory? In order to answer to these questions, the helioseismic community has worked very hard over more than 20 years to reveal the dynamical aspects of the solar interior and has put a major effort into the satellite SOHO to reach the deepest layers from where the neutrinos escape.

The helioseismic probe reveals the properties of the solar interior

The idea is simple: thanks to the movements of several millions of granules at the photospheric surface, the Sun pulsates constantly with periods around 5 minutes. By measuring with high accuracy the frequencies of thousands of acoustic modes which penetrate inside the Sun down to different depths, one may deduce information as a function of depth of some thermodynamical quantities such as the sound speed or the density.

Owing to the small amplitude of individual oscillations ($<15\text{ cm/s}$) of a spherical object like a star, one can develop the oscillations in terms of spherical harmonics $Y_l^m(\theta, \phi)$. Observations show that the surface solar oscillations consist of a superposition of a large number of modes, with degrees l ranging from 0 to more than 1500. So one has different ways to measure them. The simplest one consists in measuring the whole-disk integrated light, observing the Sun as a star. This method is used in the VIRGO experiment aboard SOHO and will be used in stellar oscillation research through three missions: the Canadian MOST mission (launch in 2003) and two European projects COROT and MONS which will be launched around 2004-2005. The ESA mission EDDINGTON will then look at the variability of several thousands of stars and detect a large number of exoplanets.

The other way, particularly adapted to the solar disk which is easily resolved, is to observe the velocity oscillations by measuring the Doppler shift of spectral lines. There are two kinds of observation: - first is the detection of the global Doppler velocity, measured by the displacement of some specific absorption lines (sodium or potassium). This method allows to detect the low degree modes ($l = 0, 1, 2, 3$) which are the most penetrating ones, as the velocity field is predominantly in the radial direction. This method has already been used in two ground-based networks: BiSON and IRIS. In the case of GOLF aboard SOHO (as in the IRIS network), we measure the global Doppler velocity shift of the sodium lines. Fig. 2 illustrates the frequency spectrum obtained by GOLF. It is the Fourier transform of the time variation residual velocity, after subtraction of the Doppler velocity due to the movements of the Sun-satellite.

- second is the detection of local velocity, separating the sun into pixels, to isolate modes of higher degrees. MDI aboard SOHO uses the nickel spectral line and obtains a Doppler image of the Sun. This instrument is extremely useful aboard SOHO as it also allows a campaign of observations from which one generates the first maps of horizontal and vertical flow velocities.

The advantage of measuring these quantities in space, at the Lagrangian L1 point, guarantees the continuity of the data along year without day/night interruption or effect of atmospheric pollution between different sites in a ground-based network. Consequently, after several years of uninterrupted accumulation of data, one may deduce a spectral answer with remarkable accuracy. This gives access to modes, with very small amplitudes and a velocity down to some mm/s, which are less perturbed by surface variability.

What have we learned from the European SOHO satellite, a joint project of ESA and NASA?

Actually, three thousand acoustic multiplets allow the determination of the differential rotation, the sound speed and the density

Fig. 2: Frequency spectrum of the acoustic modes obtained with the GOLF experiment aboard SOHO, integrated over 1 year of measurements, superimposed on an EIT vision of the Sun. The modes observed correspond to the most penetrating modes corresponding to degree $l = 0, 1, 2, 3$ (Gabriel et al. Sol. Phys. (1997) 175, 207-226). Coupled to higher degree modes, they inform on the nuclear core of the Sun.

profiles inside the Sun. The examination of these quantities is extremely useful to make progress on a dynamical vision of the solar interior and to understand the internal role of rotation and magnetic field in stars.

It has been known for a long time that the equatorial photospheric surface turns quicker than the pole regions. Due to these movements, the Sun does not present a complete spherical symmetry, consequently one observes the acoustic mode frequencies split into $2l+1$ components. In measuring such components, we have access today to latitudinal variations of the rotation down to about $0.4 R_{\odot}$ and to the superficial convective movements. This information puts limits on the internal magnetic field and contributes to the determination of the properties of the transition region between the two regimes of energy transport: radiation and convection. We call this region the tachocline region due to the rapid variation of the rotation and the transformation of differential rotation to rigid rotation. We observe a kind of shear flow in this region which induces mixing of elements and lithium destruction (Brun, Turck-Chièze and Zahn, ApJ, 525, 1032-1041, 1999). We begin also to measure a time variability of the rotation in this region with a period of about 15 months (Howe et al., Science, March 2000); if it is confirmed, it will contribute to the definitive establishment of the complex source of the magnetic-solar cycle.

We measure nowadays the solar radial sound speed profile from the surface down to 0.05 solar radius with a precision of some 10^{-5} . In comparing this profile to the theoretical profile deduced from stellar evolution (fig. 1b), we can check precisely, for the first time, the hypotheses of the calculation. The present conclusions are summarized here.

The structural equations appear extremely reasonable: the fact that no difference is observed just where the nuclear energy drops

to zero ($0.3 R_{\odot}$, see fig. 1b) confirms the theoretical idea that the Sun is today in hydrostatic equilibrium and not in gravitational collapse.

The treatment of the evolution of the internal composition is now completed to take into account not only the creation and destruction of species through nuclear reactions but also the migration of elements with time and the inhibition of such process by turbulence. Nowadays, with such improvements, we reproduce in the models the photospheric observations very well. The presence of turbulence is well established in the external layers and in the tachocline region. Nevertheless, the remaining difference between observation and theory is significant as confirmed by different instruments and techniques of inversion, and transforms the Sun into a real laboratory of physics, where we have the possibility to check the complex calculations describing the interaction of the photon with matter and the nuclear reaction rates in a plasma of high temperature and density.

The present discrepancies do not favour large dynamical effects in the solar plasma but suggest that the fundamental proton-proton interaction, governed by the weak interaction, is underestimated by no more than 2% and that the inner composition of the heavy elements is under control to better than 5% (fig. 1b). We have examined in detail different possibilities of turbulent mixing in the inner core which would have decreased the central temperature or the high energy neutrino emission and found no evidence of such process in the seismic data (Turck-Chièze, et al., Sol. Phys., vol 200). This is the first time that this conclusion can be drawn because the verification of all the physical processes needs the precision attained with SOHO. Effectively, a variation of the thermodynamic quantities by several % would have induced large variations for neutrino predictions but very tiny modifications of the sound speed (of the order of several 10^{-3}). So, in order to be sure of the nuclear density or sound speed profile, we need to verify that the acoustic mode excitation is well understood, that several biases (as asymmetry profile or magnetic perturbation) are extremely reduced. All these conditions have justified a lot of studies on the 3 instruments aboard SOHO, several tens of publications and the measurement of the lower global modes which are less sensitive to the perturbed surface as their external turning point is below.

With the present seismic results, it seems extremely difficult to invoke an astrophysical explanation for the deficit of neutrino detection on Earth (Turck-Chièze et al., ApJ lett, 2001, in press). The astrophysical and the particle physics community need now to secure the knowledge of the energy spectrum and transport of neutrinos. The most exciting idea this year is to deduce some properties of the electron neutrino from the deficit observed between the calculation of neutrino emission *deduced from helioseismology* (see fig. 1b black line) and neutrino detection on ground but we cannot ignore the presence of the strong and well organized internal magnetic field which may have some impact on the neutrino travel inside the Sun. Accompanying measurements in laboratories, such as the possibility to measure opacity cross sections with high energy lasers (LMJ in France and NIF in United States) for specific elements such as carbon, oxygen and iron would be useful to confirm the interpretation of the present seismic results and validate the extremely sophisticated calculation of photon-matter interaction (Rogers and Iglesias, in Solar Composition and its evolution- from core to corona, 1998, Kluwer Academic publishers, ed C. Fràlich, p61).

We have not yet a definitive measurement of the rotation of the core which is extremely difficult to extract from acoustic modes. The analysis of very long series of data over several years is useful not only to improve the resolution and the ratio signal/noise but

also to pass through two inherent difficulties of helioseismology, namely, the indirect effect of the stochastic excitation of the modes and of the magnetic field which both complicate the determination of the frequency. The longest lifetime modes have narrow profiles, are less disturbed by turbulent surface but have very small amplitude. Obtaining these modes could help to determine the central rotation profile. The rotation profile in the central region will give us information to determine which scenario of stellar angular momentum evolution is favoured.

The SOHO mission will still observe several years with a large benefit for stellar evolution

The main motivations of the whole seismic community is twofold:

We are gaining confidence with the ground networks and the satellite in operation in our ability to extract reliable information on the solar interior down to the nuclear region from the characteristics of the acoustic modes. But if we have now a clear dynamical vision of the Sun in the convective zone and just below (B. Fleck et al., ESA Bulletin, 102, May 2000), we have still only a static vision of the radiative zone. This is due to the inherent character of the acoustic modes. We know effectively that these modes are not the most sensitive to the solar nuclear core, since the most penetrating radial acoustic modes spend only 5% of their time in this region and their wavelength is large so one gets only mean information on a rather large region (typically 10% in mass or radius). So we are looking for another type of modes, called gravity modes which live in the radiation zone. Unfortunately, their surface velocity is less than 1 cm/s, and their long period (between one and several hours) corresponds to a range of frequency, susceptible to large perturbations by other superficial processes such as granulation, supergranulation and active solar regions. Discovering them would give better spatial resolution on the solar core and offer the possibility to access the density profile with a higher spatial resolution in the radiative interior. It would be extremely interesting also to determine the presence of instabilities which may be produced by the modes themselves in the radiative region of the Sun. Presently g-mode candidates are under study using 4 years of the GOLF instrument data and are searched for in other instruments. Confirmation of their existence will occupy the rest of the SOHO mission. We hope that the present Sun is not too active and that good data are delivered around the solar maximum.

Another interest in continuing the SOHO observation for several more years, is to confirm through the solar maximum the understanding of the internal pulse of the dynamo in the Sun. The variability of the solar rotation in the tachocline region must be firmly confirmed by observations over time. If it is the case, it will be a key point in the understanding of solar and stellar activity.

At the beginning of a new century, we may say that helioseismic data have demonstrated our ability to probe a star down to its core. We have verified in detail and extended the hypotheses of stellar evolution established purely theoretically in the twenties. It is a very great success of the astrophysical community that demonstrates its ability to work at very high accuracy (some 10^{-5} on data and 10^{-2} on physical processes). If we succeed also in the next two goals (central rotation and internal solar dynamo), we will be able to describe to what extent the Sun, a very common star, is a dynamical object. This will be fundamental to building a bridge between very dynamical objects (young stars), slowly evolving stars (at the hydrogen burning stage) and stars at the final dynamical stage of stellar evolution, by introducing naturally the influence of rotation and magnetic field in astronomical objects.

One may really say that we are now able to see deeply inside the sun; the next step will be the exploration of other stars.