

Monitoring stellar evolution of low-mass stars with seismology

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ABSTRACT

Context. Draft-draft, currently with the A&A L^AT_EX package, but with a form suitable (?) for a large-audience journal. [**Nature, Science or A&A letter?**]

Aims. The Sun, currently a quiet star burning hydrogen in its core, is known to evolve in 5 billions years into the red giant phase, corresponding to a rapid extent and cooling of its envelope. Before that, it will enter the subgiant phase, when exhaustion of hydrogen in the central region provokes the contraction of the helium core to ensure the equilibrium of the star. These steps of stellar evolution are well known. However, determining the evolutionary status of a given field star may be complex, since up to now classical fundamental stellar parameters are unable to provide clear markers of evolution. Now, with asteroseismology, this identification becomes quite obvious, since we have access to an new observable parameter that probes directly the stellar core.

Methods.

Results.

Conclusions.

Key words. Stars: oscillations - Stars: interiors

Seismic data from space missions

As a consequence of the photometric observations provided by the space missions CoRoT and Kepler, solar-like oscillations have been revealed in thousands of stars (De Ridder et al. 2009; Chaplin et al. 2011). These oscillations, excited by the convective flux carrying the stellar luminosity in the uppermost stellar layers, have tiny amplitudes. Since they correspond to acoustic modes, with pressure acting as a restoring force, their frequencies are, approximately, natural harmonics of the characteristic frequency determined by the mean stellar density (Eddington 1917). This frequency is called large separation, since it is approximately determined as the frequency spacing between consecutive radial oscillation modes. Combined with the frequency of maximum oscillation amplitude, which is proportional to the surface gravity field, and to the stellar effective temperatures [ref], this important seismic parameter provides estimates of the stellar mass and radius [ref], with the asymptotic correction (Mosser et al. 2012a).

Gravity modes

Recently, oscillation modes mostly hidden in the Sun have been revealed in subgiants and red giants (Beck et al. 2011; Benomar et al. 2012). They correspond to the signature of a dense radiative core. In such a stellar core, gravity waves are trapped, distinct from pressure modes, with buoyancy acting as a restoring force. They occur at frequencies that are comparable to the pressure modes in the stellar envelope, so that they can couple efficiently. Hence, even if the gravity modes are not directly observable, since they are deeply trapped in the core, they give rise to mixed modes,

propagating as gravity waves in the core and as pressure waves in the envelope. These mixed modes are a wonderful way to distinguish red giants burning helium in their core from less-evolved giants burning only hydrogen in a thin shell surrounding the core (Bedding et al. 2011) since they reveal the properties of the core. They were also used to determine the rotational profile of the red giants (Beck et al. 2012).

As pressure mode frequencies are harmonics of the large separation $\Delta\nu$, the periods of gravity modes are multiple of a given period that represents the core properties, called period spacing and noted $\Delta\Pi_1$ (Tassoul 1980). Recently, it has been made possible to measure very precisely the period spacing in a large amount of red giants (Mosser et al. 2012b) and subgiants (Benomar et al. 2012). As a result, independent of the complete analysis of the oscillation spectra, we have access to two characteristic seismic parameters. The large separation $\Delta\nu$ indicates the mean stellar density, whereas the period spacing $\Delta\Pi_1$ indicates the core evolution. Examining the variation of $\Delta\Pi_1$ as a function of $\Delta\nu$ allows us to monitor the stellar evolution and to clearly distinguish the different evolutionary stages. This was done for a set of subgiants and red giants observed with Kepler, with masses mainly in the range from 0.8 to 1.5 solar masses, where mixed modes are observed (Figure 1).

Subgiant stage

A star quits the main sequence when the hydrogen fuel is exhausted in its core. In a low-mass star, with a mass less than $1.5M_{\odot}$, the observation of mixed modes indicates the

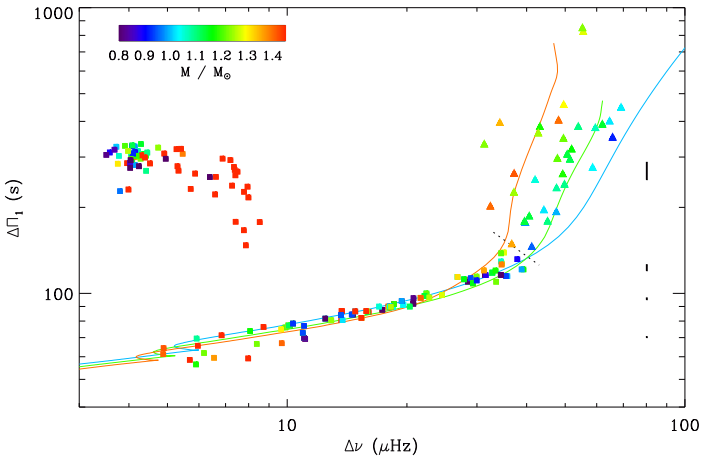


Fig. 1. Seismic diagram showing the period spacing $\Delta\Pi_1$ as a function of the large separation $\Delta\nu$. The seismic proxy of the stellar mass is also indicated by the color code. The seismic proxy of the radius is also indicated on the upper x-axis, for a $1.1 M_\odot$ star [à faire]. Subgiants are indicated by triangles, red giants by square, with a limit given by the dashed line. Evolutionary tracks are provided by [tbd, ref]. The error boxes on the right side indicate the mean uncertainties, as a function of $\Delta\Pi_1$.

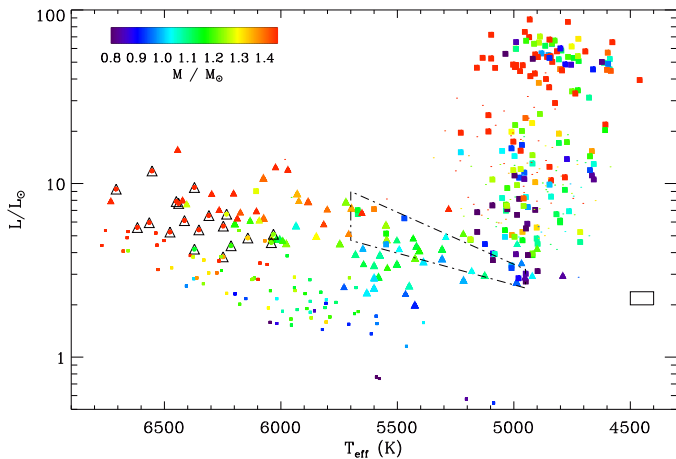


Fig. 2. HR diagram of the stars presented in Fig. 1. The domain defined by the dashed line, much larger than the error box in the bottom-right corner, includes both subgiants and giants. [+ add main-sequence stars, in order to show the difference between main-sequence stars and subgiants, see with Bill.]

presence of a dense radiative core, and the beginning of the subgiant phase, as is the case for Procyon (Bedding et al. 2010). The slow contraction of the core, according to the Kelvin-Helmholtz mechanism, implies the extent of the envelope [ref]. Hence, the mean stellar density decreases, and the large separation decreases too. As subgiants evolve, $\Delta\nu$ keeps decreasing and the period spacing $\Delta\Pi_1$ decreases similarly, as a consequence of the core contraction. Stars with different mass or metallicity behave in a different way. If, according to stellar modelling, one assumes that the value of the gravity spacing indicates the core mass, one gets from the $\Delta\Pi_1 - \Delta\nu$ relation (Figure 1) that, at fixed $\Delta\Pi_1$, low-mass stars have a larger $\Delta\nu$ than stars with a higher mass since their radius is significantly smaller too, so that their mean density is larger. Thus, we note a clear mass dependence explaining the gradient in the $\Delta\nu - \Delta\Pi_1$ re-

lation. At this stage, subgiants have kept the memory of their different origin on the main sequence.

From subgiants to the red giant branch

Following the stellar evolution, indicated by the decrease of the large separation together with the increase of the stellar radius, we note the convergence of the evolutionary tracks in the seismic $\Delta\nu - \Delta\Pi_1$ diagram. According to stellar evolution, the properties of the stellar core becomes increasingly dominated by the properties of the isothermal (?) helium core [ref]. This cannot be seen with the classical stellar parameters that are used for constructing the Hertzsprung-Russel diagram (Figure 2). On the contrary, the evolution from the subgiant to the red giant phase is clear in the $\Delta\nu - \Delta\Pi_1$ diagram: independent of the initial conditions, all subgiants with the same mean density have the same core properties. The physics of the red giant branch explains this.

Red giant branch

The red giant phase is known to be governed by the physical properties of the thin hydrogen-burning shell between the helium core and the envelope, where the stellar luminosity is produced. The temperature and density of this shell are intrinsically linked to the mass of the pure helium core. Its pressure, which supports the stellar envelope, is then fixed. As a consequence, the structural properties of the envelope are also fixed. Independent of the mass, all stars with a similar helium core, hence the same period spacing $\Delta\Pi_1$, have the same total mean density, hence the same large separation $\Delta\nu$. From the $\Delta\nu - \Delta\Pi_1$ diagram, the evolution from the subgiant to the red giant phase is made clear: the subgiant phase stops and the red giant phase starts when the initial characteristics of the stars are diluted by the physical conditions governing the red giant evolution. Another degeneracy occurs in a later evolution stage. After the helium flash, all low-mass stars have all very similar $\Delta\nu$ and $\Delta\Pi_1$, around $4 \mu\text{Hz}$ and 300 s respectively (Mosser et al. 2012b).

Conclusion

For the first time, we have an unambiguous marker of the stellar evolution, and especially for the transitions between the main sequence and the subgiant, and the subgiant and red giant phases. The complete analysis of the stars presented in the $\Delta\nu - \Delta\Pi_1$ diagram, based on the complete analysis of their oscillation spectra and not only on the global seismic parameters, will allow us to closely link the classical stellar structure parameters used in the HR diagram to the seismic parameters, so that the determination of the evolutionary status will become much easier for all low-mass stars.

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