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Recent CoRoT Achievements in Stellar Physics

Annie Baglin,[1] Eric Michel,[1] and Arlette Noels[2]

[1]*LESIA, Observatoire de Paris, 5 pl. J. Janssen, 92195 Meudon, France*
Unité de Recherche du CNRS UMR 8109, associée à l'Université Paris VI
Pierre et Marie Curie et à l'Université Paris VII Denis Diderot

[2]*Institut d'Astrophysique et de Géophysique, Université de Liège,*
Allée du 6 Août 17, 4000 Liège, Belgium

Abstract. The CoRoT (Convection Rotation and Planetary Transits) satellite has spent almost six years in space. We present here a global overview of observations already made and then focus on some of the important results which are not described extensively elsewhere in these proceedings. It is a compilation of different investigations, not yet assembled into a global vision. It is probably too early to form a global overview, as it generally takes two or three years from the release of data before early physical interpretations can be made!

1. What Has Been Observed Up to Now ?

Since the previous Hakone conference in 2011, the CoRoT project has continued to collect data, and the scientific community has used them extensively. At the time of the present meeting, the instrument suddenly stopped delivering data; although the prospect of a repair remained for a while, it unfortunately proved to be impossible. We will not increase our dataset any further, but we still have a lot to do with the existing one.

After 2136 days in orbit, the initial programme, as described in Baglin et al. (2007), has been completed and several new and often unexpected issues explored. A total of 163682 stars have been observed, including 156 bright ones ($V \leq 9.5$), in twenty-six different pointings, all lying inside the two CoRoT "eyes", centered at the intersection of the Galactic Plane and Equator (Auvergne et al. 2009).

2. How Have the Data Been Already Used ?

CoRoT data are available as soon as they have been corrected for instrumental effects, and not later than six months after the end of the observations, at the Mission Archive hosted at Orsay, France:

Institut d'Astrophysique Spatiale (IAS): `http://idoc-corot.ias.u-psud.fr/` .

Three mirrors have been installed at :

National Aeronautics and Space Administration Star and Exoplanet Database (NStED)
`http://exoplanetarchive.ipac.caltech.edu/applications/ETSS/CoRoT_astero_index.html`,
Laboratorio de Astrofísica Espacial y Física Fundamental (LAEFF):
`http://sdc.cab.inta-csic.es/corotfa/jsp/searchform.jsp`, and

Centre de Données astronomique de Strasbourg (CDS):
`http://vizier.u-strasbg.fr/viz-bin/VizieR?-source=B%2Fcorot` .

As of 2012 October 28th, the number of downloads of public data has been almost constant and of the order of 3000 per year (Fig. 1); queries have come from all over the world, with a very large proportion coming from countries contributing to the mission and from the United States. Up to now, there are more than 400 publications in Class A journals using CoRoT data.

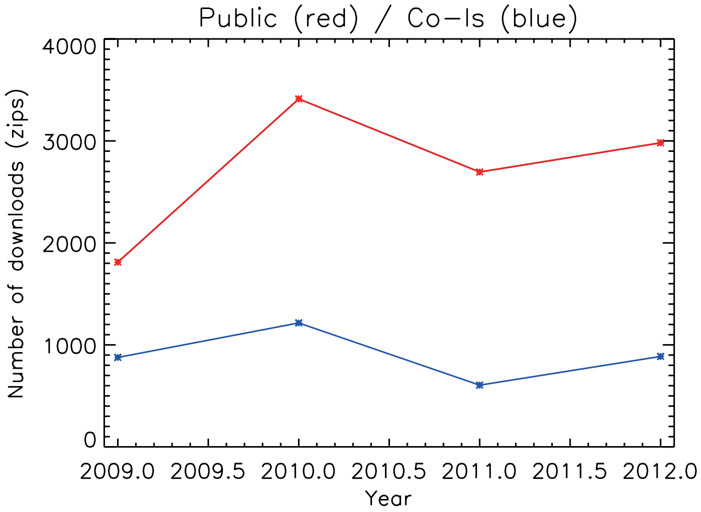

Figure 1. Number of compressed downloads (zips) of CoRoT data from the IAS Archive, as a function of time (in red public data, in blue private data).

3. A CoRoT Niche: The Young Objects

CoRoT had a unique opportunity to observe young regions in zones where continuous observations were possible, essentially in the anticenter direction. It contains very young stars and clusters. A special focus has been made on several young clusters, for instance NGC 2264, NGC 2244, Dolitze 25, and IC 4756.

3.1. A Young Cluster: NGC 2264

This young (10^7 years old) and close-by cluster has been observed twice. After a first very successful twenty-five days of observation by CoRoT in 2008 (SRa01), a worldwide campaign called "Coordinated Synoptic Investigation" (CSI) was organised in 2011 by John Stauffer. It involved four spacecraft (MOST*, CoRoT, Spitzer and Chandra) and thirteen terrestrial observatories (Cody et al. 2013). It acquired forty days

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*Microvariability and Oscillations of Stars

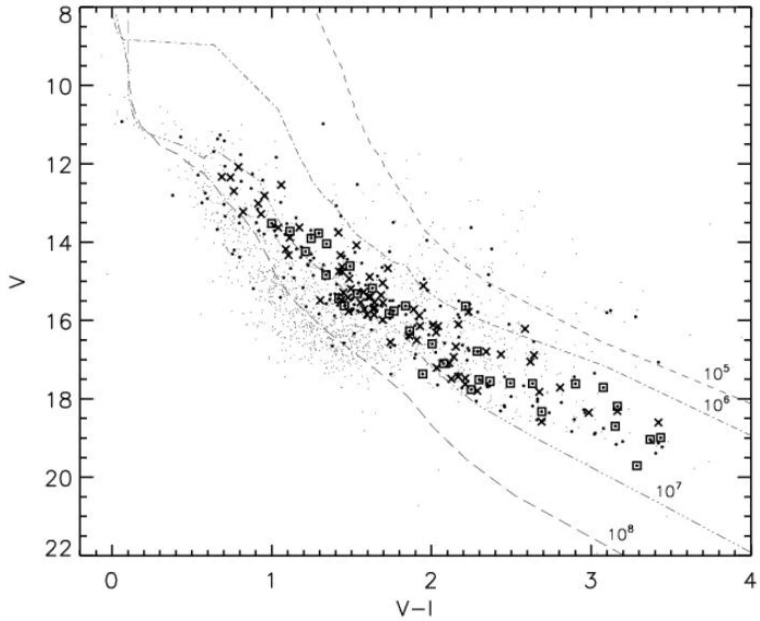

Figure 2. Color magnitude diagram of stars observed by CoRoT in the NGC 2264 region. The black dots indicate the confirmed 301 cluster members, crosses are Weak-Lined T Tauri (WTT) stars and squares are Classical T Tauri (CTT) stars, compared with isochrones, from Affer et al. (2012).

of optical monitoring from CoRoT (SRa05) and MOST, thirty continuous and simultaneous days of mid-infrared time series from Spitzer, some X-ray observations with Chandra, and complementary spectroscopic and photometric data from ground-based telescopes.

CoRoT and MOST observed continuously, and the CoRoT light curves produced a very precise time basis, with which the Spitzer and Chandra shorter exposures could be correlated. The sky coverage of the CoRoT detector (1.2 × 1.2 degrees), allows all proposed targets to be observed at the same time, on the same detector. More than 300 confirmed cluster members have been targeted (Fig. 2).

These high-precision, high-cadence photometric data sets from the X-ray through near-infrared are shedding light on physical mechanisms of variability and reveal the properties of otherwise unaccessible inner disk regions. The high-resolution spectroscopic data (sometimes simultaneous) obtained for many targets is enhancing our knowledge of this young phase of star formation. Not all the data are completely analyzed yet, but there are already many new outcomes, sometimes unexpected.

3.1.1. Dynamics of the Accretion Disks

Temporal variations, attributed to the obscuration of stellar light by material accumulated by the interaction of an inclined stellar magnetosphere and inner disk region, show different classes of behavior: AA Tau like, Spot like, and Accretor (Fig. 3). The quality of the correlation between the optical and infra-red fluxes indicates the degree of coherence of the disk (Alencar et al. 2012).

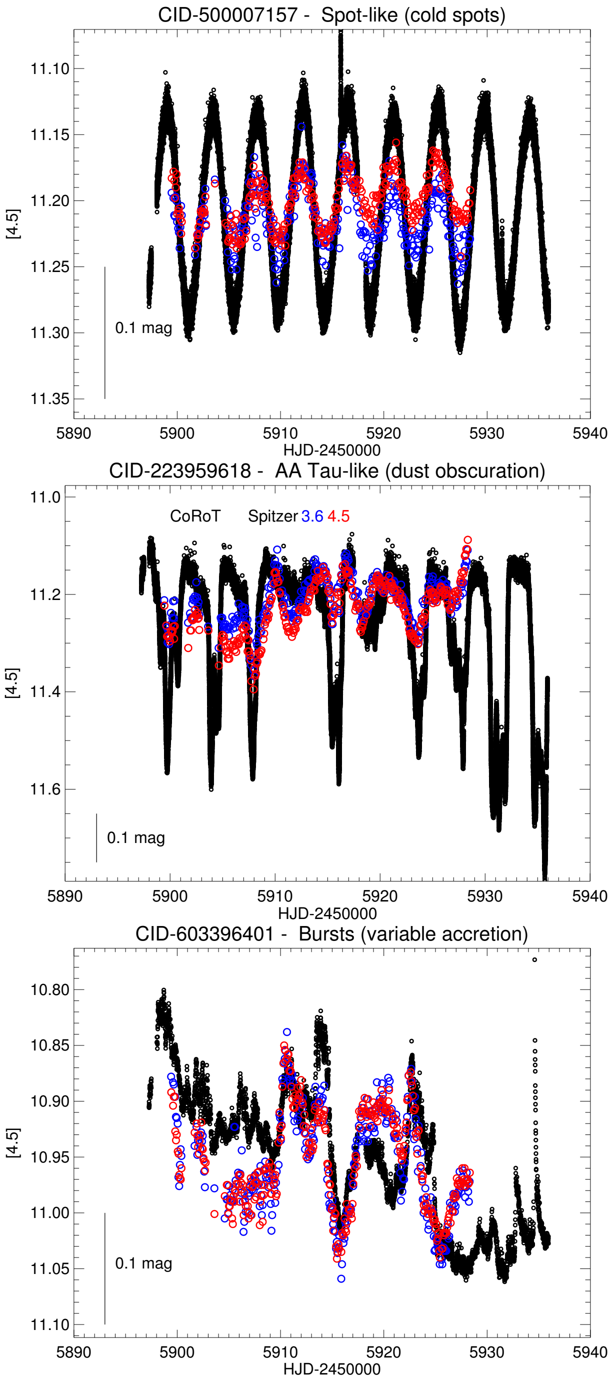

Figure 3. Light curves of young CTTs from Spitzer at 3.6 and 4.5 μm, superimposed on those obtained with CoRoT (black), showing three different types of behavior; *top:* spots (essentially rotation), *middle:* AA Tau like (dust obscuration), and *bottom:* variable accretion (bursts), from Alencar et al. (2012).

3.1.2. Detection of Flares

Thanks to the simultaneity of observations by CoRoT, Spitzer and and Chandra, it has also been possible to associate some events in CoRoT light curves with stellar flares (Fig. 4). These simultaneous multi-band observations of the heating pulse at the origin of the flare (by CoRoT and Spitzer) and of the cooling phase (by Chandra) allow the physics of flare heating, response of the heated and evaporated plasma, a relation with characteristics of the involved coronal loops, and a possible relation between flares and accretion disks to be investigated. These are the first multi-band observations of these events (Flaccomio 2013).

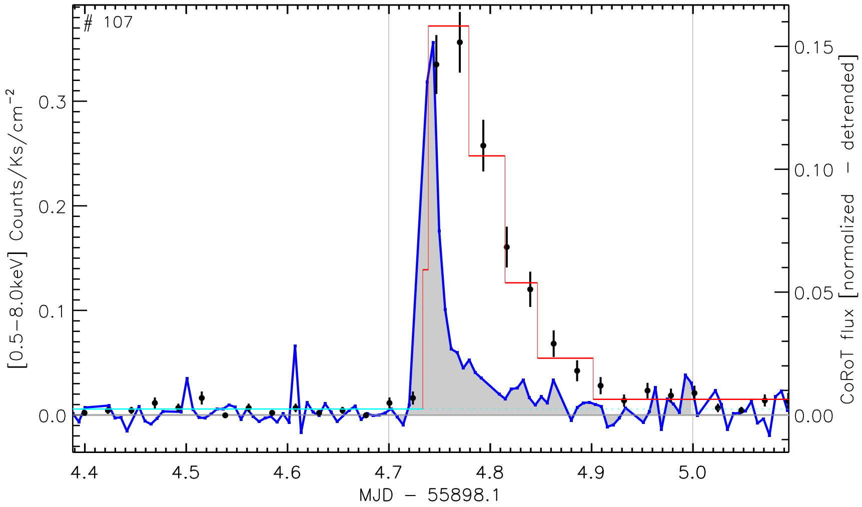

Figure 4. An example of a flare observed simultaneously with CoRoT and Chandra. The grey area marks the CoRoT flare, while crosses indicate the X-ray measurements (red segments are a representation of X-ray data with a maximum likelihood analysis to identify "constant" intervals).

3.1.3. Pulsations in Pre-Main Sequence (PMS) Stars

A significant number of PMS stars have been targeted during these campaigns for which seismology studies are now possible. Combining data from the two runs of CoRoT on this cluster, γ Doradus-type pulsations have been detected for the first time in two quite bright NGC 2264 members in the PMS phase (Zwintz et al. 2013). The detected frequencies below $\sim 10\,\mu$Hz seem to be caused by a combination of rotation and g-mode pulsation (Fig. 5).

3.2. A Young and Active Star

Many CoRoT fields contain young stars. One of them (CID 102899501) has been precisely characterized by Gondoin et al. (2012). The fundamental parameters of this K0 V star are $T_{\rm eff} = 5180\,$K, $\log g = 4.35$, [M/H] = 0.05, corresponding to a $1.09\,M_{\odot}$ star still in its PMS phase.

The strong Ca II and Balmer emission and the strong Li absorption line indicate an age of 8.3 Myr. Spot modeling from the CoRoT light curve, which covers fifty-four

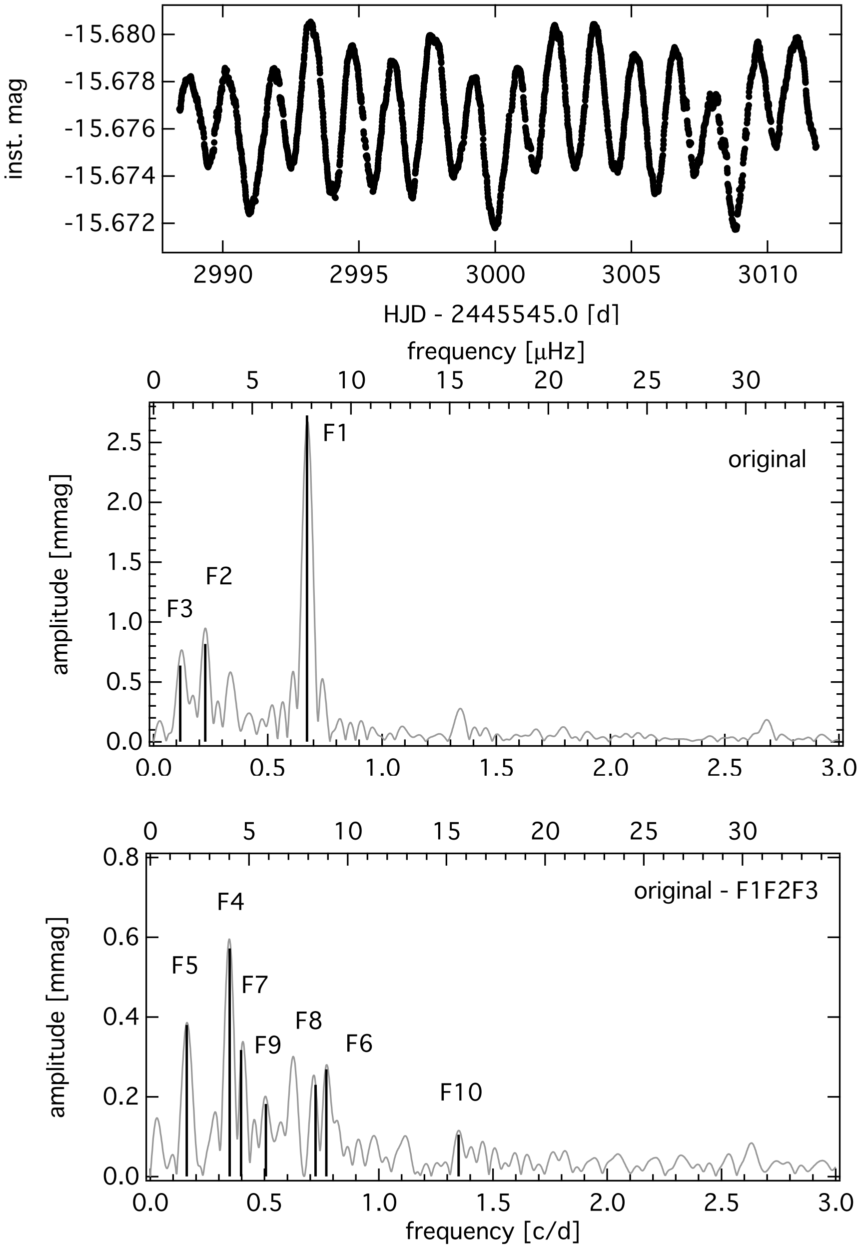

Figure 5. CoRoT light curve of the PMS star VAS 20 (top), the Fourier transform showing the three major components (middle) and the lower amplitude modes after subtracting the three major ones (bottom), from Zwintz et al. (2013).

days, determines the rotation period to be 1.65 days, a spot coverage of 10%, a spot lifetime of 1.45 days, and no evidence of differential rotation. Its high level of activity, and high rotation rate are indicators of its youth. It probably represents the status of young solar-type stars, at the time of planet formation. It constitutes the first direct estimate of the level of activity at this early stage of fast rotation, and documents a time evolution model of chromospheric activity on the Main Sequence.

4. Rotation

The almost continuous CoRoT light curve allows periodic low frequency modulations to be measured. Such periodic features could be attributed to the rotation of an inhomogeneous stellar surface, which may contain spots. If the rotation origin is confirmed, the measured period is the true rotation period of a star, without an inclination effect. But, as stressed by De Medeiros et al. (2013), these period determinations at very low frequencies need care, if rotation is to be distinguished from possible binarity, intrinsic variability and even instrumental effects.

There has already been extensive work to determine these "rotation periods", generally complemented by wide ground-based surveys of all targets to determine effective temperatures and gravities. Several teams [see, e.g., Affer et al. (2012); do Nascimento et al. (2012); De Medeiros et al. (2013)] are producing such results, either on individual objects or on a statistical basis.

4.1. The Sun in Time

Special emphasis has been given to stars following the Sun's evolutionary track from the Main Sequence towards the giant branch. More than 4000 measurements of (semi-sinusoidal) variability periods for CoRoT stars have been performed by De Medeiros et al. (2013). They are combined with ground-based observations to determine fundamental parameters with an accuracy of 0.05 for $\log g$ and 400 K for $T_{\rm eff}$ (Fig. 6). This wide sample allows a precise calibration of the rotation rate decrease along the giant branch, for comparison with predictions of models proposing different mechanisms for this spin down.

4.1.1. Rotation in the Solar Neighborhood

A catalogue of more than 1700 rotational velocities has been produced using CoRoT observations in different directions in the Galaxy. Though there is instrumental bias in the sample, it is possible to use rotation as a proxy for age, and Affer et al. (2012) identify a set of rapidly rotating stars, considered as very young (~ 600 Myr), and showing that the star formation process in the solar neighborhood is still ongoing (Fig. 7).

4.1.2. Statistics of Rotation in NGC 2264

Using CoRoT data from the CSI campaign, as described previously, Affer et al. (2013) have shown that rotational distributions of CTT and WTT stars are different, suggesting a difference in the rotational properties of accreting and non-accreting stars. If confirmed, it would provide an estimate of the angular momentum transfer between the disc and the star (Fig. 8).

4.1.3. Transport of Angular Momentum

do Nascimento et al. (2012) have used rotation periods of a well studied sample of thirty-five subdwarfs to test the efficiency of angular momentum transport as a star evolves towards the giant branch. The rotation periods are determined from CoRoT

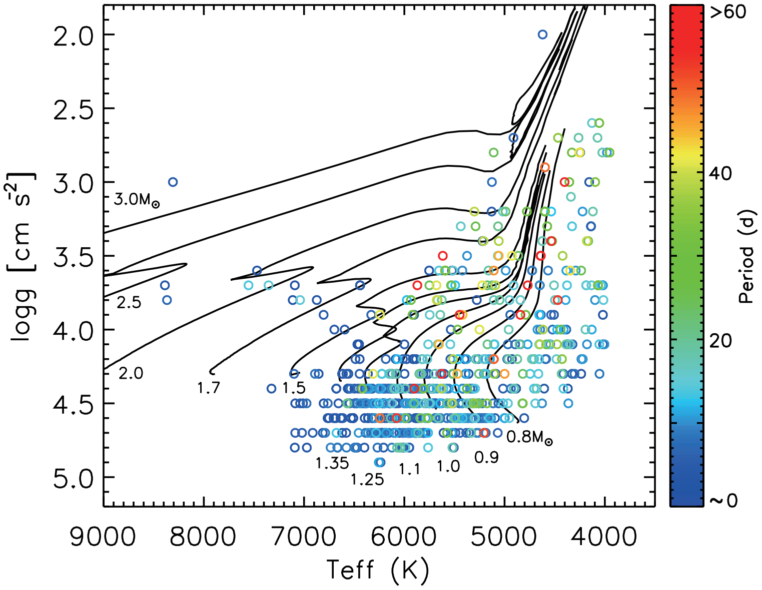

Figure 6. Hertzsprung Russell (HR) diagram of a recent sample of rotation periods measured using CoRoT data (De Medeiros et al. 2013); $\log g$ and $T_{\rm eff}$ are from the spectroscopic study of Sarro et al. (2013). Open circles denote this sample, where measured periods are represented with different colors, corresponding to the color bar at the right-hand side. Theoretical tracks from Ekström et al. (2012), which include predictions for the transport of angular momentum following the prescription of Zahn (1992), are depicted by the solid curves for different masses (identified by black labels), from Leão et al. (2013).

light curves and combined with color indexes. They remain almost constant from the Main Sequence to the giant stage. This behavior is compared with theoretical evolutionary sequences computed assuming solid body rotation, and with sequences including rotation induced mixing due to both meridional circulation and the transport of angular momentum produced by rotational instabilities (Zahn 1992). In this case, rotation is driven by the deepening of the convective zone, which extracts angular momentum from the inner reservoir, and compensates for the radius increase.

There is a clear agreement with the predicted sequence of models including differential rotation (Fig. 9). On the other hand, evolutionary models computed with solid body rotation predict rotation periods which increase even more rapidly with age. See do Nascimento et al. (2012), their figure 4.

5. Seismology along the Main Sequence

5.1. Solar-like Oscillations in Solar Analogs

As foreseen, CoRoT has observed a tenth of the bright stars having mass and evolutionary stages close to those of the Sun. However, it is still extremely difficult to observe real solar twins.

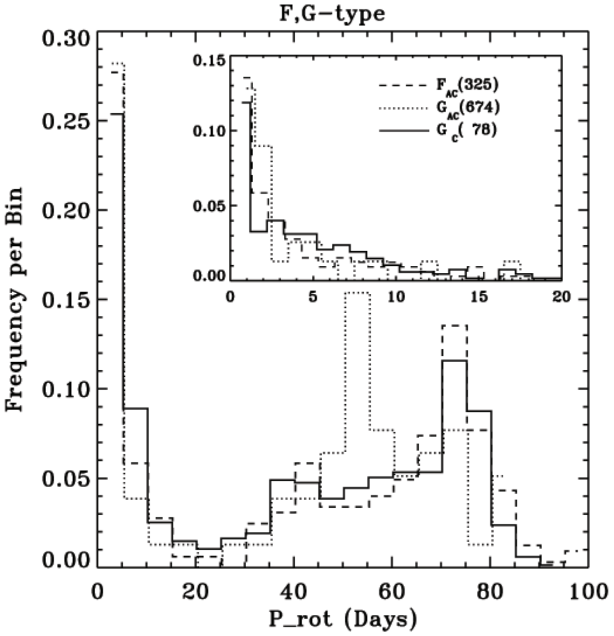

Figure 7. Normalized distribution of rotation periods for the sample of F- and G-type stars, from Affer et al. (2012).

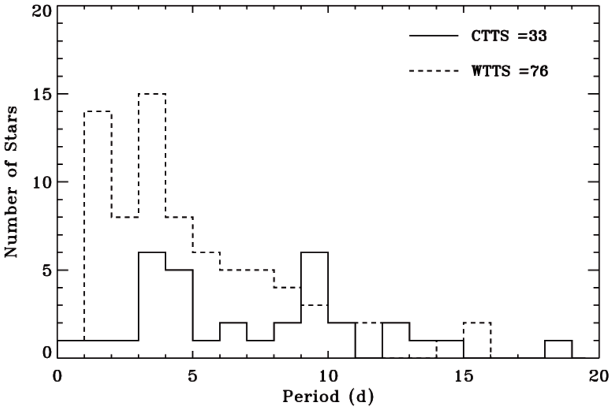

Figure 8. Rotation periods of T Tauri stars in NGC 2264, where the distinction between CTT and WTT distributions is obvious.

As seen in Fig. 10, they all show pressure mode oscillations in the range 1 − 4 mHz. The large separation is precisely determined. In some cases modes are detected up to $\ell = 3$ (see also the García and Mathur contributions in these proceedings).

The star closest to the Sun, in terms of fundamental parameters, is the so-called "solar sister" HD 42618. It has a mass of $0.9\,M_\odot$, a radius of $0.92\,R_\odot$ and a large frequency separation of $142\,\mu$Hz (Barban et al. 2012).

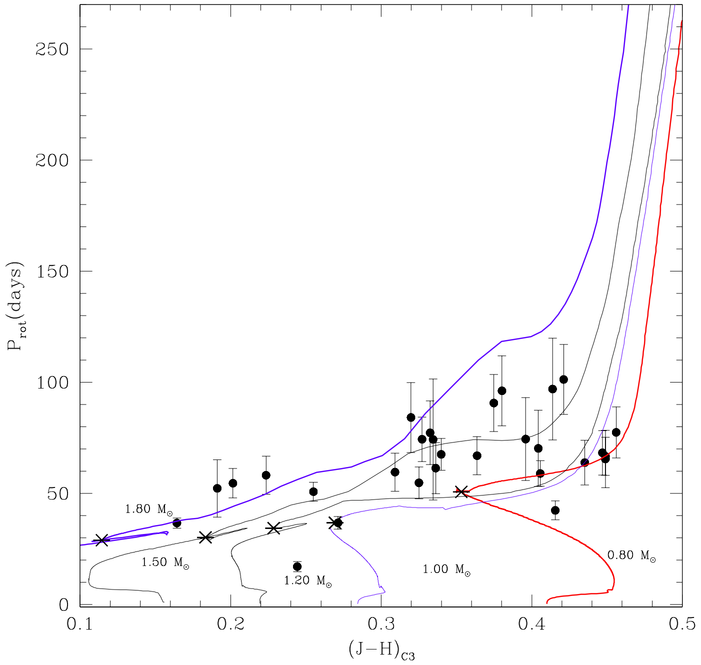

Figure 9. Rotation period evolution of a sample of subgiants measured from CoRoT light curves as a function of the $(J-H)$ index, compared with model predictions assuming differential rotation and internal transport of angular momentum. The models are shown as continuous lines for [Fe/H]=0 and different stellar masses, with the beginning of the subgiant branch being flagged with an asterisk, from do Nascimento et al. (2012).

Seismic signatures of penetrative convection have been estimated for different stars. The best case is HD 52265 in which the periodic signal of the ratios rr_{01} and rr_{10} as a function of frequency is more pronounced than in the Sun, and with a longer period (Lebreton & Goupil 2012). The extent of the penetrative convection at the base of the convective zone in terms of H_p and normalized radius is more precise. A best fit of the proxy is $d_{\text{ov}} = 0.95 \pm 0.08 H_p$. HD 52265 is similar to the Sun in all aspects except for the higher metallicity. Therefore, to understand the difference between the two stars, it is important to investigate the impact of metallicity on the structure and dynamics of the tachocline.

5.2. B Stars

The population of the anticenter observable zone of CoRoT is quite young and contains many O and B stars. In hot B stars, variability at low frequency is sometimes difficult to characterize. Is it due to spot modulation by rotation, g-type pulsations, or a mixture of these effects? For several objects, CoRoT data are complemented by ground-based spectroscopic observations, for the determination of fundamental parameters, but also for the characterisation of variability.

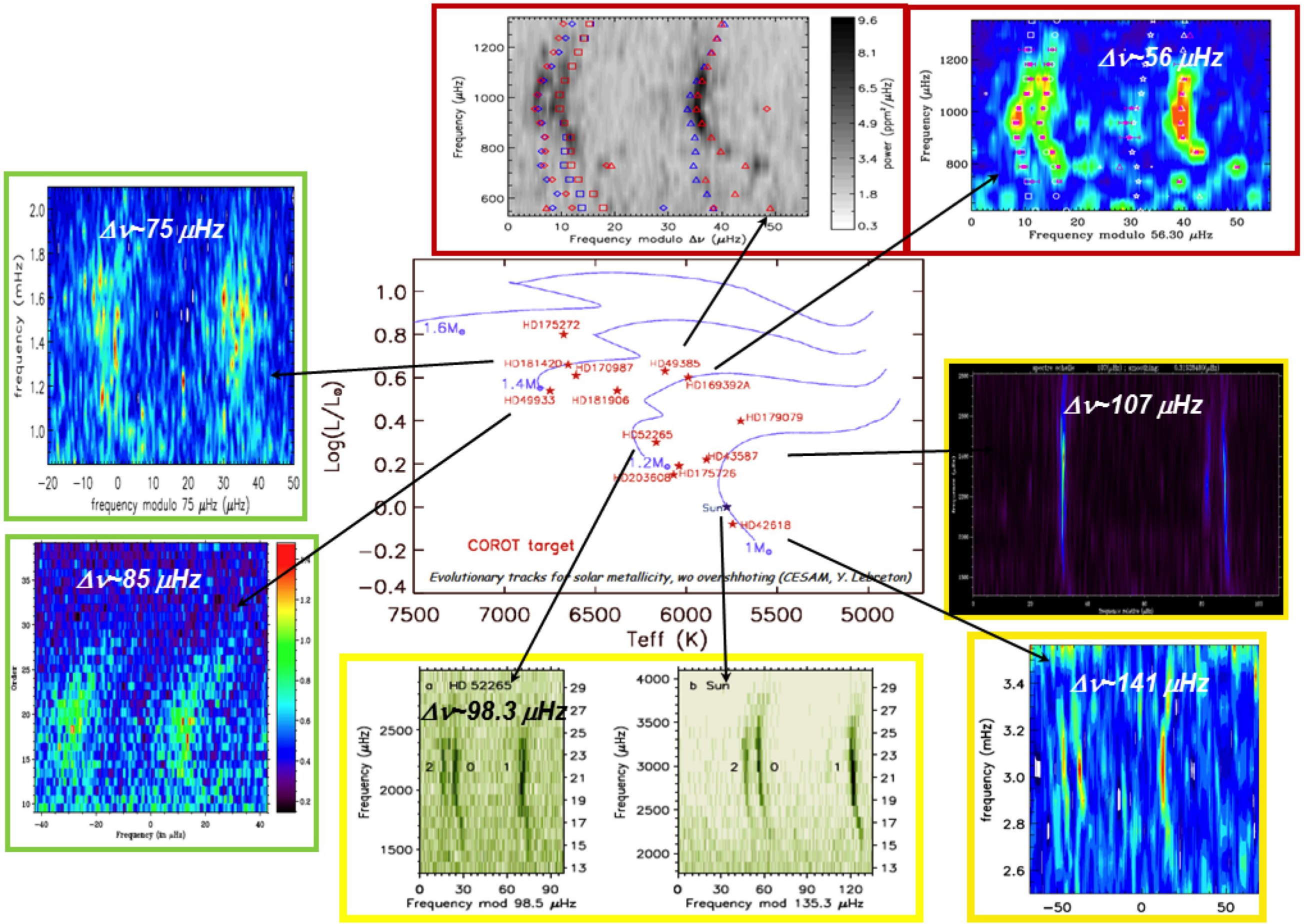

Figure 10. The echelle diagram of several solar like CoRoT targets and their position in the HR diagram.

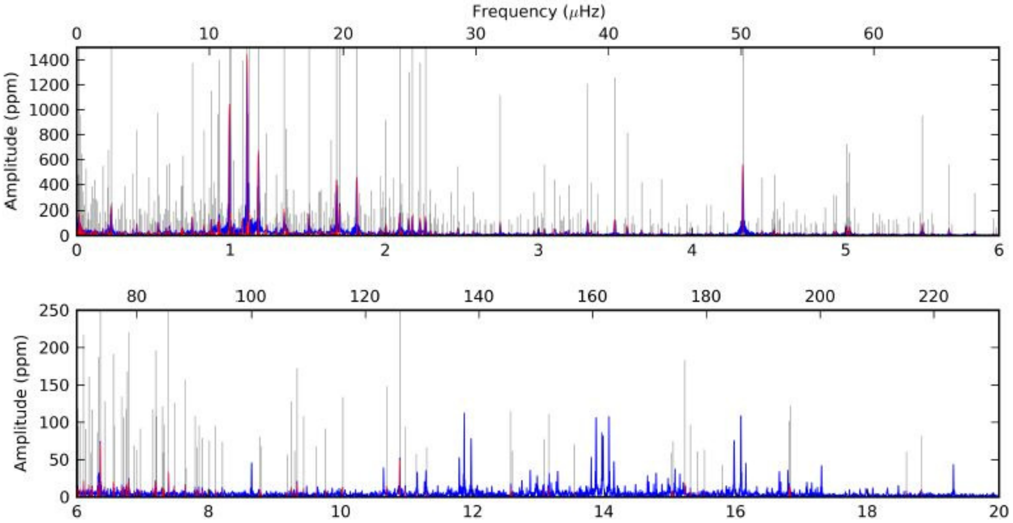

Figure 11. Scargle periodogram of the full CoRoT light curve of HD 43317, showing 424 frequencies (red vertical lines) (repeated in grey in the background after multiplying the amplitude by ten for better visibility).

In the very fast rotator HD 43317, a B3 IV star rotating at 50% of the break-up speed, Papics et al. (2012) have detected equal period spacings at low frequency revealing probable gravito-inertial modes (Fig. 11).

Aerts et al. (2013) analyzed the CoRoT light curve of HD 46769, a B5 II star and concluded that the modulation (of the order of 100 ppm) was due only to rotation (Fig. 12). There are no signs of pulsation at the 1 ppm level, which is consistent with the fact that the star lies outside any instability strip. But surprisingly, it does not show any significant macroturbulence, contrary to most evolved variable B supergiants, which badly need very large macroturbulence to explain their spectral line wings.

In the Be star HD 51452, Neiner et al. (2012) have detected 189 frequencies in the range between 0 and 4.5 c/d. The main frequencies are also recovered in the spectroscopic data. Many of these frequencies are in the domain of gravito-inertial modes and cannot be excited by the κ-mechanism, but these modes can be stochastically excited in the convective zones. Such gravito-inertial modes had never been observed in any star, and theory predicted that their very low amplitudes would be undetectable even with CoRoT. It is suggested that amplitudes are enhanced because of the very rapid stellar rotation. In addition, it seems that the amplitude variations of these modes are related to the occurrence of minor outbursts of the Be phenomenon.

5.3. The Intermediate Mass Puzzle

After a long period of scepticism on the possibility of interpreting the extremely rich pulsation amplitude spectrum of the δ Scuti stars (Fig. 13), a new paradigm is appearing, based on the detection of quasi-regular spacing in frequency, as developed for instance by Paparó and Suarez in these proceedings.

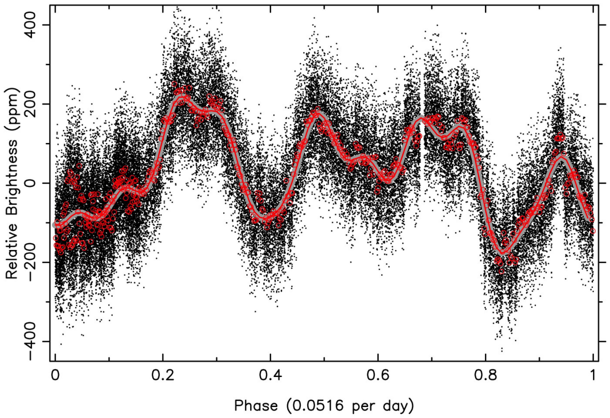

Figure 12. The linearly detrended CoRoT light curve of HD 46769 phased with respect to the frequency $f = 0.0516\,\mathrm{c/d}$; the thick grey full line is a harmonic fit with f and seven harmonics. The red symbols and the red line denote averages over ten consecutive data points and a fit to that binned light curve.

6. The CoRoT Red Giant Programme: Mapping and Dating the Galaxy

CoRoT has set the stage for this completely new field in asteroseismology with the first paper of De Ridder et al. (2009). As first shown by Mosser et al. (2010), the strong homogeneity of the oscillation pattern of red giants allows the use of global seismic parameters, which obey simple scaling laws. An automated efficient ensemble seismology is then possible and is now extensively developed.

The structure of red giants at various stages of their evolution, before and after the Helium Flash, has been analyzed in detail and linked to the properties of their frequency spectra (see Noels and Montalbán in these proceedings, and reference therein).

One of the major contributions of CoRoT is the possibility of calibrating these scaling laws by observing bright members of the class in its seismology field. In particular CoRoT has observed four red giants, probable members of the cluster NGC 6633, and also a red giant in a well known eclipsing binary HD 169689.

Though the calibrations of the global seismic indexes is efficient, difficulties are still pending concerning the amplitudes. Samadi et al. (2012) have shown the importance of non-adiabatic effects in the extended envelopes of red giants, which prevent the adoption of a simple and unique scaling all the way from the Main Sequence (see also Grosjean et al., these proceedings).

The second important contribution of CoRoT is its ability to observe in different directions, in the inner and outer parts of the Galaxy. CoRoT has targeted approximately 35 000 red giants up to 10 kpc from the Sun (Fig. 14). This mapping is now blossoming. It needs complementary measurements of the fundamental parameters, and this is being done through cooperation with ground-based surveys such as the APO[†] Galactic Evolution Experiment (APOGEE) and the European Southern Observatory (ESO) GAIA Public Spectroscopic Survey.

[†] Apache Point Observatory

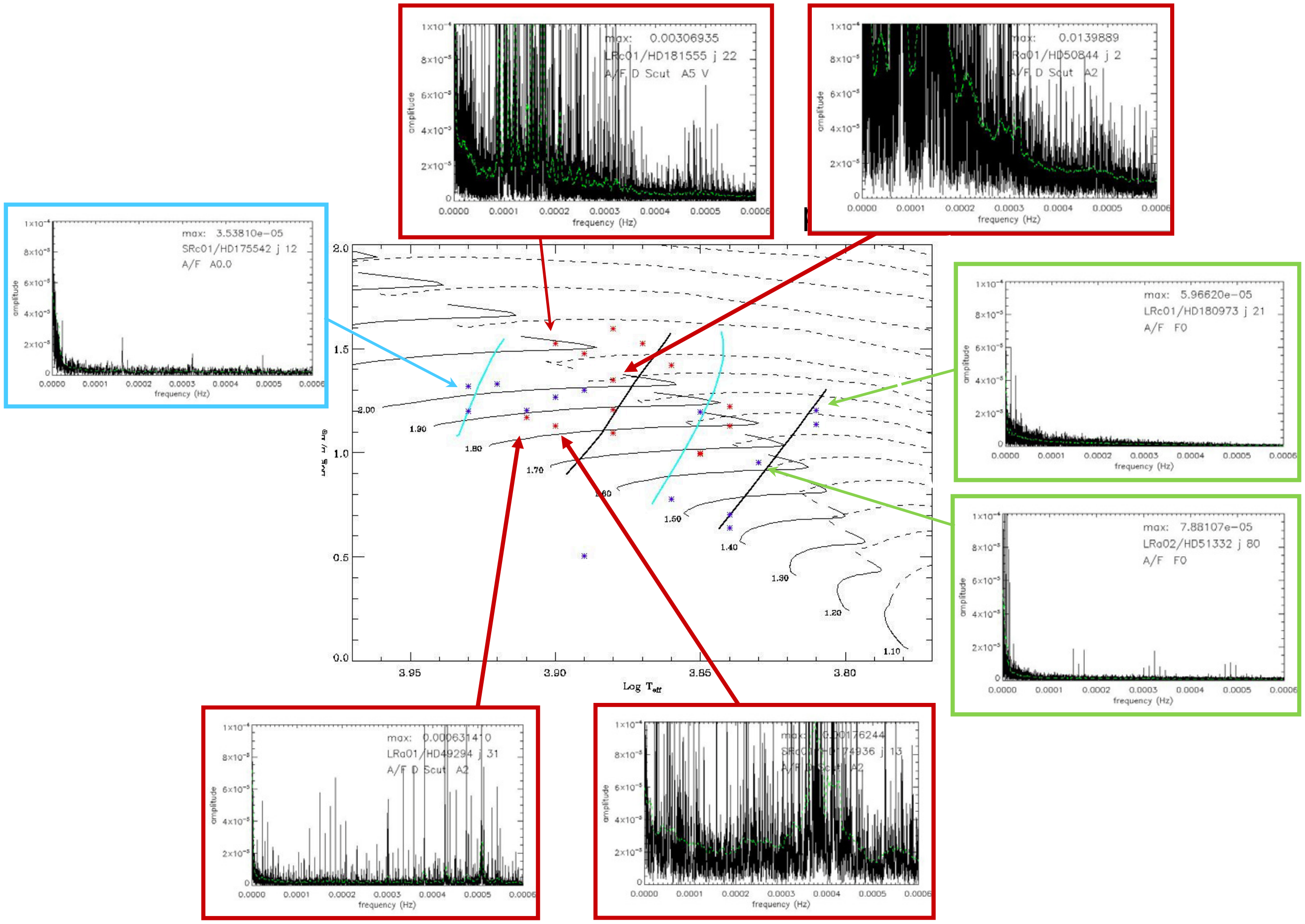

Figure 13. Bright stars in the δ Scuti instability strip or observed nearby with CoRoT (crosses). A few spectra drawn at the same scale illustrate the strong diversity of the power detected at low frequency, possibly due to either pulsation or granulation or both.

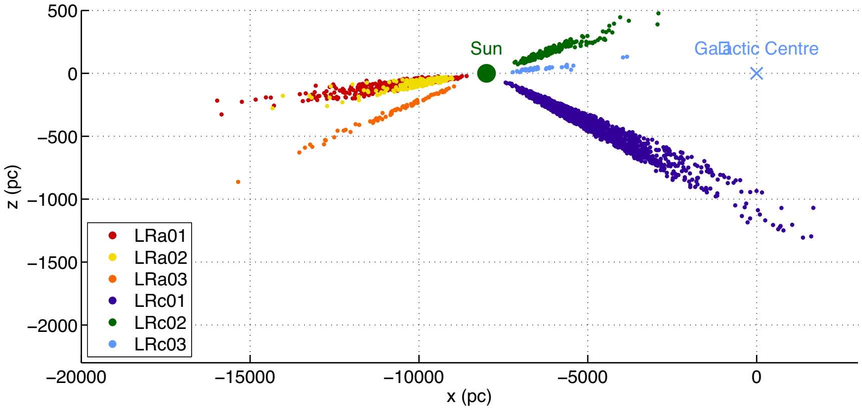

Figure 14. The Regions of the Galaxy accessed by both CoRoT and *Kepler*.

Using calibrations giving a proxy for the age, Miglio et al. (2013) show that significant differences appear in the histogram of the ages of red giants, in three different fields, LRa01, LRa02 and LRc01 (Fig. 15). The two anticenter histograms are quite similar, while the center one is quite different, with a smaller fraction of young stars and a larger fraction of older ones. To confirm this result, some more work is needed to chase the observational bias!

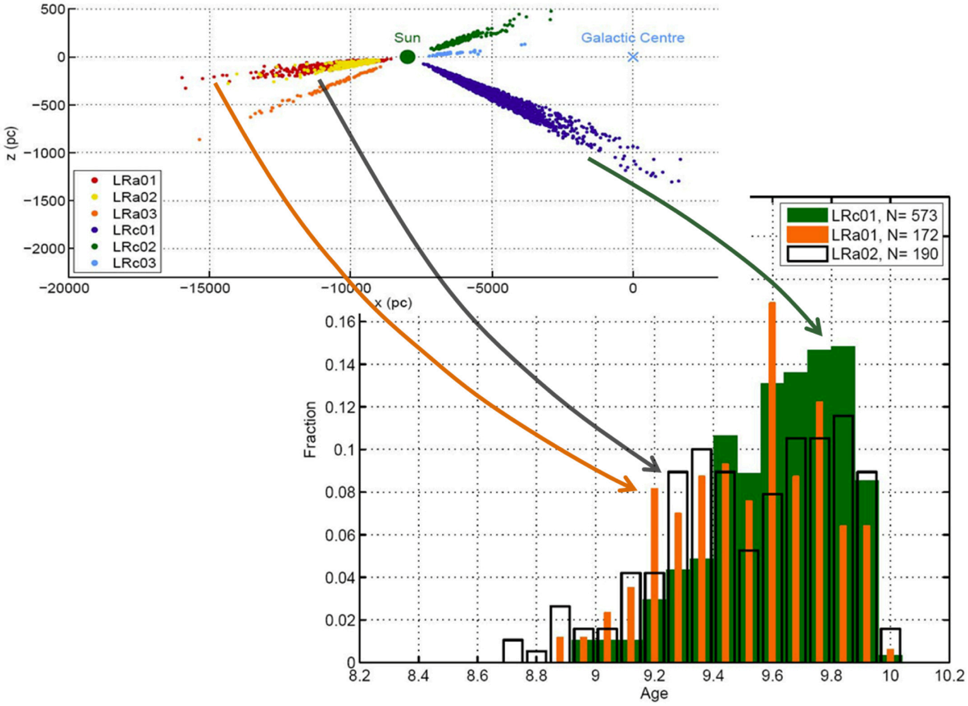

Figure 15. Populations of red giants distinguished by CoRoT, in the three runs LRa01, LRa02 and LRc01.

7. Classification of Stellar Variability

The CoRoT Variable Classifier, as developed by Debosscher et al. (2009) has been much improved. The use of fundamental parameters derived from high resolution power spectra, with the goal to improving the variability classification obtained using information derived from CoRoT light curves only, is very fruitful (Sarro et al. 2013). And only rough estimates of the parameters are needed, because most variability types that overlap in the space of time series parameters are well separated in the space of physical parameters (e.g., γ Dor / SPB[‡] or δ Scut / β Cep stars).

8. Conclusion

Stellar high precision photometry from space, with long and continuous observations, by MOST first and then by CoRoT and *Kepler*, have produced data of extremely high quality. These instruments have been designed to fulfill the very demanding constraints based on what we knew about helioseismology. Now the situation has changed drastically. We have understood that these data which detect variability of the stellar flux often at the micromagnitude level, can be used in many different fields of stellar physics.

We have already achieved some steps forward, mostly in stellar hydrodynamics as expected. We have started to learn about internal rotation, transport of angular momentum, penetrative convection, core overshooting, interaction between pulsation, activity, bursts, about the early stages of star formation, and their interaction with their debris disks. We also found a new way to study the structure and the evolution of our Galaxy.

These first projects have shown the way. Stellar variability at the micromagnitude level, and in particular asteroseismology, is not only a basic tool for understanding stellar evolution but also for mapping the Galaxy and understanding its evolution. Good luck to future missions!

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