Seismology Working Group

Evolution and Seismic Tools Activity

ESTA

Mário João P.F.G. Monteiro
and the ESTA Team

ESTA goals

ESTA has been setup in 2002, following the AO by ESA to select 4 Co-Is for CoRoT. ESTA is part of the *Seismology Working Group* and aims at contributing towards the preparation and exploration of the scientific results of CoRoT.

In order to achieve this, the goals set for ESTA included:

- to provide a **grid of reference stellar models and their frequencies** of oscillation.
- to extensively **test, compare and optimize numerical tools** used to calculate:
  - stellar models,
  - oscillation frequencies,
  - and seismic inversions.

The ultimate objective of ESTA for CoRoT is to secure that numerical uncertainties/errors in the models correspond to uncertainties in the frequencies below the expected observational precision. The interpretation of the frequencies should only depend on the physics of the models!

Adopted strategy

- To make **as much information as possible available** on:
  - evolution codes,
  - seismic codes,
  - data produced by these tools.

- To **initiate coordinated activities**, aiming at inducing the development of the codes and the discussion of the physical assumptions used in these codes, by:
  - setting specific tasks,
  - facilitating the exchange of data,
  - establishing new collaborations.

- To **produce and make available reference data** useful for asteroseismology of stars across the HR diagram, namely:
  - evolution sequences,
  - stellar models,
  - oscillation frequencies.

All information regarding past and ongoing activities, as well as data and documents, is available at the **ESTA Website**:

www.astro.up.pt/corot/

Participants

Belgium:
Andrea Miglio
Josefina Montálban
Arlette Noels
Richard Scuflaire
Sylvie Théado
Anne Thoul

France:
Annie Baglin
Gabrielle Berthomieu
Matthieu Castro
Stephane Charpinet
Marie Jo Goupil
Alan Hui-Bon-Hoa
Yveline Lebreton
Eric Michel
Pierre Morel
Pascal Lambert
Bernard Pichon
Janine Provost
Sylvie Vauclair

Denmark:
Michael Bazot
Jørgen Christensen-Dalsgaard

Germany:
Achim Weiss

Italy:
Scilla Degl'Innocenti
Maria Pia di Mauro
Marcella Marconi
Pier Giorgio Prada Moroni
Alessandra Ruoppo
Paolo Ventura

Portugal:
Margarida S. Cunha
João M. Fernandes
João P. Marques
Mário J.P.F.G. Monteiro
Christian W. Straka
Teresa C. Teixeira

Romenia:
Marian D. Suran

Spain:
Rafael Garrido
Andy Moya
Juan Carlos Suárez

Switzerland:
Patrick Eggenberger

United Kingdom:
Ian W. Roxburgh
Michael J. Thompson

Participation was open to all colleagues from *CoRoT contributing countries* willing to join the comparison and having access to an evolution or/and seismic code.

Up-to-date lists of participants and tools are maintained at the ESTA webpage. There is also a distribution list for emails used to exchange news on ESTA related activities.

Evolution Tools

- **ASTEC** - *Aarhus Stellar Evolution Code*
  By: J. Christensen-Dalsgaard
- **ATON** - *Rome Stellar Evolution Code*
  By: P. Ventura et al.
- **CESAM** - *Code d'Evolution Stellaire Adaptatif et Modulaire*
  By: P. Morel & Y. Lebreton
- **CLÉS** - *Code Liégeois d'Evolution Stellaire*
  By: R. Scuflaire, J. Montálban, and the BAG
- **FRANEC** - *Frascati Raphson Newton Evolutionary Code*
  By: S. Degl'Innocenti, M. Marconi et al.
- **GARSTEC** - *Garching Stellar Evolution Code*
  By: A. Weiss & H. Schlattl
- **GENEC** - *Geneva Evolution Code*
  By: P. Eggenberger et al.
- **STAROX** - *Roxburgh's Stellar Evolution Code*
  By: I. Roxburgh
- **TGEC** - *Toulouse-Geneva Evolution Code*
  By: A. Hui-Bon-Hoa et al.
- **YREC** - *Yale Rotating Stellar Evolution Code*
  By: C. Straka et al.
- ...

Seismic Tools

- **ADIPLS** - *Aarhus Adiabatic Pulsation Package*
  By: J. Christensen-Dalsgaard
- **FILOU** - *Meudon Oscillation Code*
  By: J. C. Suárez
- **GraCo** - *Granada Oscillation Code*
  By: A. Moya & R. Garrido
- **LNAWENR** - *Romanian Oscillation Code*
  By: M. Suran
- **LOSC** - *Liège Oscillation Code*
  By: R. Scuflaire et al.
- **NOSC** - *Nice Oscillations Code*
  By: J. Provost
- **OSCROX** - *Roxburgh's Oscillation Code*
  By: I. Roxburgh
- **POSC** - *Porto Oscillation Code*
  By: M. Monteiro
- **PULSE** - *Canadian Stellar Oscillations Code*
  By: P. Brassard & S. Charpinet
- ...

Conversion tool

In order of facilitate the comparison and exchange of models a conversion tool has been implemented: **MODCONV**. The objective is to include all formats used within ESTA for producing models and as input for the oscillation codes. More formats will be added as necessary.

The conversions already available are:

[12]	GONG	-|FGONG	[23]	FGONG	-|OSC	[32]	OSC	-|FGONG
[13]		|OSC	[24]		|AMDL	[34]		|AMDL
[14]		|AMDL	[25]		|FAMDL	[35]		|FAMDL
[15]		|FAMDL	[26]		|SROX	[36]		|SROX
[45]	AMDL	-|FAMDL	[62]	SROX	-|FGONG			
[54]	FAMDL	-|AMDL	[64]		|AMDL			
			[65]		|FAMDL			

The possibility to re-mesh the models when formatting the input for the oscillation codes is also being added.

ESTA documents:

- "*Description of the File Formats used within CoRoT/ESTA*" (2005-12-05)

Milestones

The previous reports/events relevant for ESTA are:

- *Meeting 0 (CoRoT Week 3), Dec. 2002*
  - 1 oral presentation (+ posters)
- *Meeting 1 (CoRoT Week 7)* , Dec. 2004
  - 1 oral presentation (+ 1 discussion + posters)
- *Meeting 2 (CoRoT Week 8)*, May 2005
  - 1 discussion (+ 1 report + posters)
- *Meeting 3 (Workshop in Nice), Sep. 2005*
  - 16 oral presentations + 2 discussions (+ 2 reports)
- *Meeting 4 (Workshop in Aarhus)*, Oct. 2005
  - 17 oral presentations + 2 discussions (+ 2 reports)
- *Meeting 5 (CoRoT Week 9)*, Dec. 2005
  - 4 oral presentations + 2 discussions (+ 1 report + posters)
- *Meeting 6 (CoRoT Week 10)*, Jun. 2006
  - 3 oral presentations + 2 discussions (+ posters)
- *Meeting 7 (Workshop in Porto)*, Nov. 2006
  - 23 oral presentations + 3 discussions + 2 work sessions (+ posters)

Almost all **code builders have used this work to correct, develop and optimize** the evolution and seismic codes being compared!

Reference specifications

In order to define a common reference for all codes we have selected a reference set of specifications for the grids and comparisons. Namely,

- **initial parameters**:
  - physical constants,
  - astronomical constants,
  - initial abundances of the elements and heavy elements mixture;
- **input physics**:
  - equation of state,
  - opacities,
  - nuclear reaction rates,
  - convection and overshooting,
  - atmosphere,
  - microscopic diffusion.

As found during the comparisons, small differences in any of these can mask the numerical effects we wanted to test with this exercise.

Reference physics

ITEM	Selection	References
EoS	OPAL	Rogers et al. (1996, 2001 Tables)
Opacities	OPAL + AF	Iglesias & Rogers (1996) Alexander & Fergusson (1994)
Reaction rates	NACRE	Angulo et al. (1999)
Convection	MLT (α = 1.6)	Bohm-Vitense (1958) + Henyey et al. (1965)
Overshoot	*none or* α_{ov}=0.15	Fully mixed + adiabatic stratification
Diffusion/settling	*none*	-
Mixture	Solar	Grevesse & Noels (1993)
Atmosphere	Grey	Eddington's

Detailed specifications of the physics can be found at:

http://www.astro.up.pt/corot/compmod/docs/Task1_Roadmap.pdf

The reference grids

Evolutionary sequences, models and frequencies have been made available by different groups:

1) **CoRoT CESAM-ADIPLS** grid by Y. Lebreton & E. Michel (2000): models were calculated with CESAM (2K) while the frequencies were determined with ADIPLS.

All data (sequences, selected models and their frequencies) are available for download from webpage http://wwwusr.obspm.fr/~lebreton/Modeles/CESAM.html.

2) **CoRoT CESAM-POSC** grid by J. P. Marques, J. Fernandes, M. J. P. F. G. Monteiro (2006): models were calculated with CESAM (2K) while the frequencies were determined with POSC. The full PMS evolution from the birth-line has been included.

All data (sequences, selected models and their frequencies) are available for download from the ESTA webpage http://www.astro.up.pt/corot/. Additional models and frequencies can be provided on request.

3) **CoRoT CLÉS-LOSC** grid by J. Montálban, A. Miglio, A. Noels, R. Scuflaire (2007): models were calculated with CLÉS while the frequencies were determined by LOSC.

4) Other grids (high mass stars, etc) have also been made available with slightly different physics.

Definition of Tasks

In order to organize the activities on code optimization different tasks have been organized:

- **Task 1** - on model comparison (Chair: M. Monteiro)

The goal was to compare the evolution codes for representative values of stellar mass and age in order to achieve an acceptable level of consistency between different codes.

- **Task 2** - on frequency comparison (Chair: A. Moya)

The goal was to compare the seismic codes for specific stellar models to secure an accurate calculation of the oscillation frequencies.

- **Task 3** - on model comparison with microscopic diffusion (Chair: Y. Lebreton)

The goal is to compare the evolution codes when microscopic diffusion of chemical elements is included.

Task 1 - model comparison

Under this task a few **specific, fully identified, stellar cases** have been proposed in 2002 to compare the evolution codes.

The physical assumptions proposed as the reference for the comparison have been defined and stellar models at different stages of evolution have been identified in order to cover as much as possible a representative range of stellar mass and age.

The comparison has addressed **how the physics and the numerical implementation of the physics may affect the result of different codes**. Discrepancies have been used to optimize and develop the codes in order to produce consistent outputs between codes.

Both the global stellar parameters of the selected models and their interior structure have been compared. The evolutionary sequences leading to each model and the seismic properties were also compared under this Task.

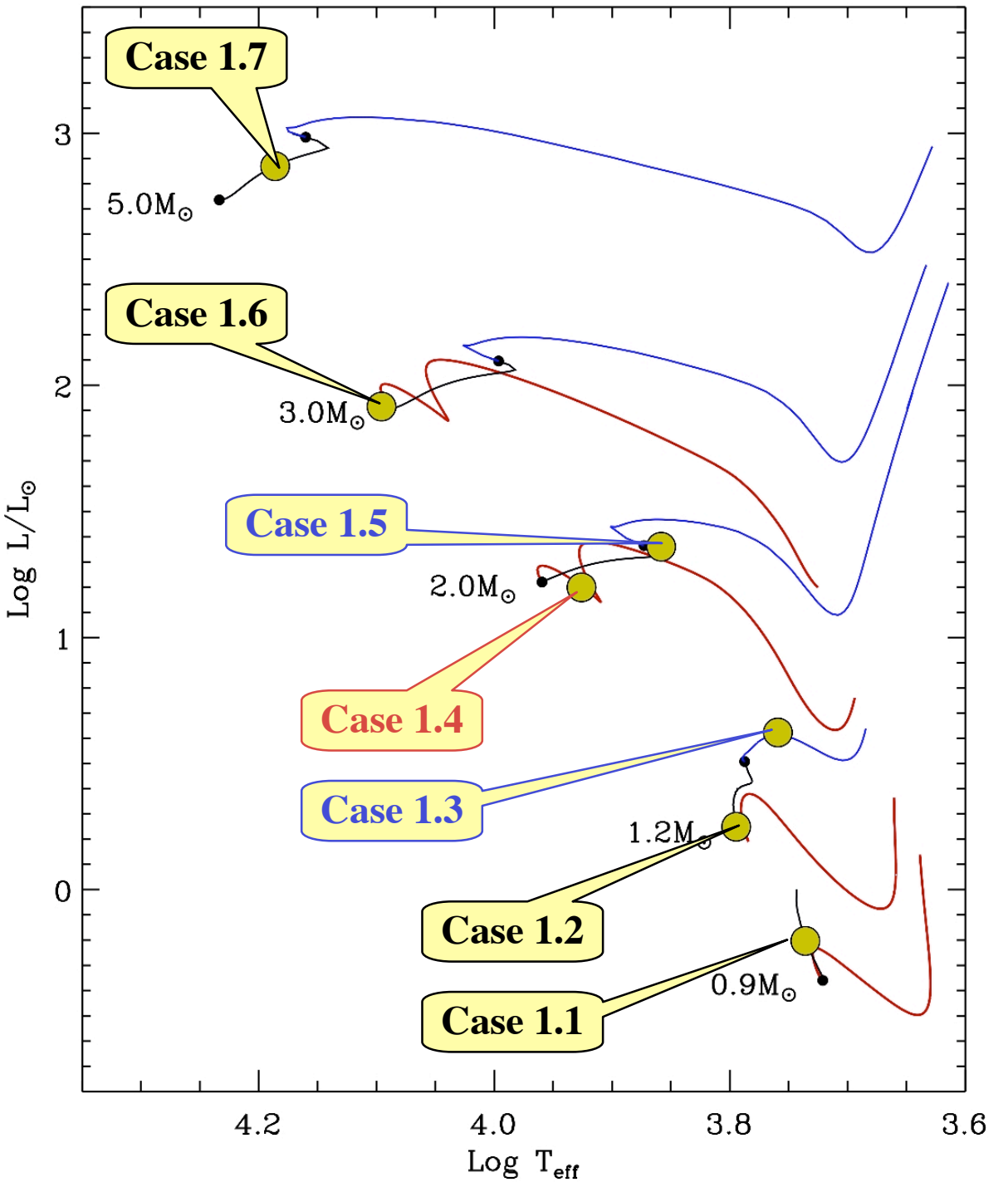
Further details are given at the following webpage:

www.astro.up.pt/corot/compmod/task1.html

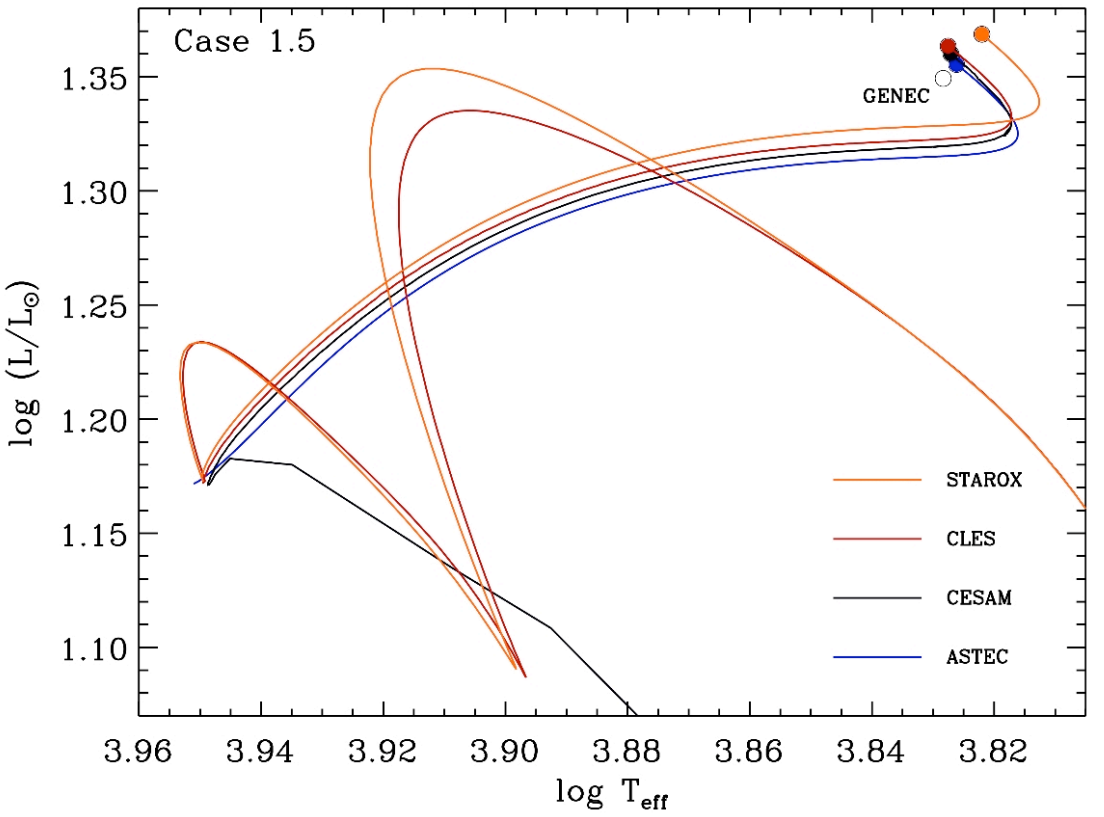
Targets

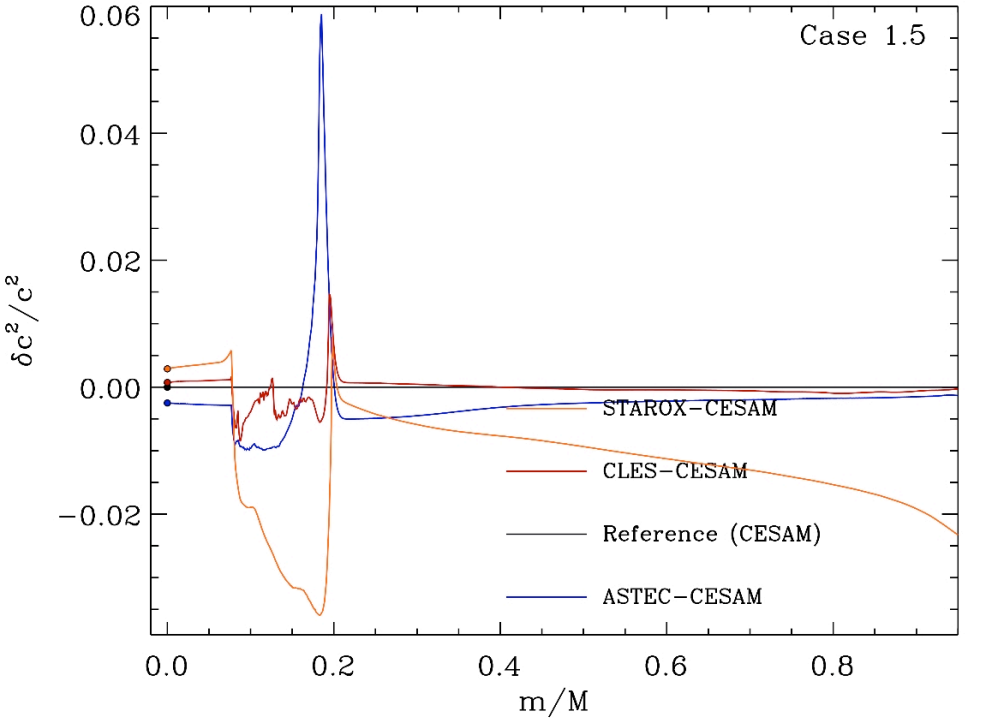
Case	$M/M_\odot$	Y_0	Z_0	α_{OV}
1.1	0.9	0.28	0.02	-
1.2	1.2	0.28	0.02	-
1.3	1.2	0.26	0.01	-
1.4	2.0	0.28	0.02	-
1.5	2.0	0.26	0.02	0.15
1.6	3.0	0.28	0.01	-
1.7	5.0	0.28	0.02	-

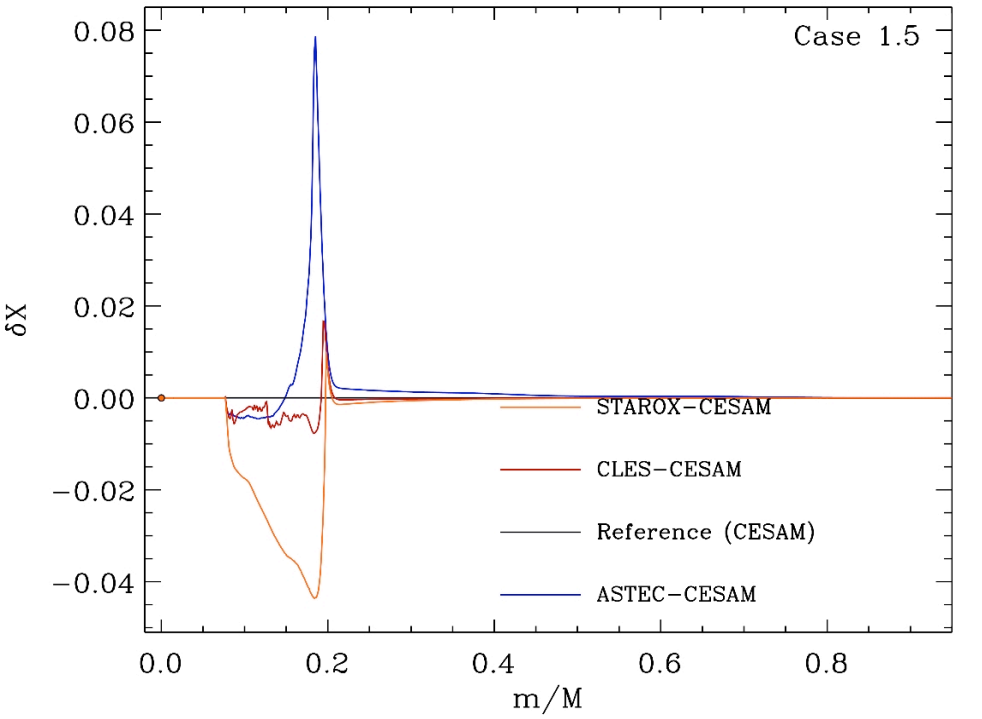
Case	X_C	T_C	$M_{He,Cor}$	State
1.1	0.35	-	-	MS
1.2	0.69	-	-	ZAMS
1.3	-	-	$0.1M_\odot$	PostMS
1.4	-	$1.9\ 10^7$	-	PreMS
1.5	0.01	-	-	TAMS
1.6	0.69	-	-	ZAMS
1.7	0.35	-	-	MS



Case 1.5







End of the main sequence (TAMS) model:

M = 2.0 $M_\odot$

Code	Age	R/Rsun	L/Lsun	Teff	Tc/10^7	rhoc
ASTEC	1 175,4	3,5390	22,668	6 701,2	2,7869	130,900
CESAM	1 184,1	3,5427	22,909	6 715,5	2,7937	131,757
CLES	1 202,4	3,5491	23,090	6 722,6	2,7971	131,684
STAROX	1 207,7	3,6627	23,369	6 637,4	2,8024	131,832
Spread	2,7%	3,4%	3,0%	1,3%	0,6%	0,7%

Monteiro et al (2006)

Task 1 - major results

After iteration it has been possible to obtain that **if the codes follow closely the same specifications** then the

- global parameters are consistent to within a few percent,
- internal structure differs by less than 1%,
- frequencies can differ by about 1 μHz.

Some evident problems (to be solved!):

- the estimated ages can be very different!
- evolution of the edge of convective regions (in particular with overshoot and semi-convection) is not adequately handled!
- near-surface layers and atmosphere!

Task 2 - frequency comparison

Andy Moya leads this task with the objective of comparing the frequencies (linear & adiabatic) as calculated by different seismic codes for the same model. The goal is to establish the numerical accuracy of the seismic codes and their sensitivity to some of the calculation parameters. To do so several steps are part of this exercise:

Step 1: comparison of the frequencies from different seismic codes for the same model.

In this task, models of the same star have been study in order to quantify the uncertainty on the numerical precision of the seismic parameters for these stars. The models used were for a **1.2 M_{Sun} main sequence star** with two different distribution of mesh points: 2k and 4k.

Step 2: comparison of the frequencies from the same seismic code for different models of the same stellar case provided by different equilibrium codes.

Step 3: comparison of the frequencies for specific pulsators.

The first results for Task 2 have been prepared for publication. Further details on this Task are given at the following webpage:

`www.astro.up.pt/corot/compfreqs/task2.html`

Task 2 - major results

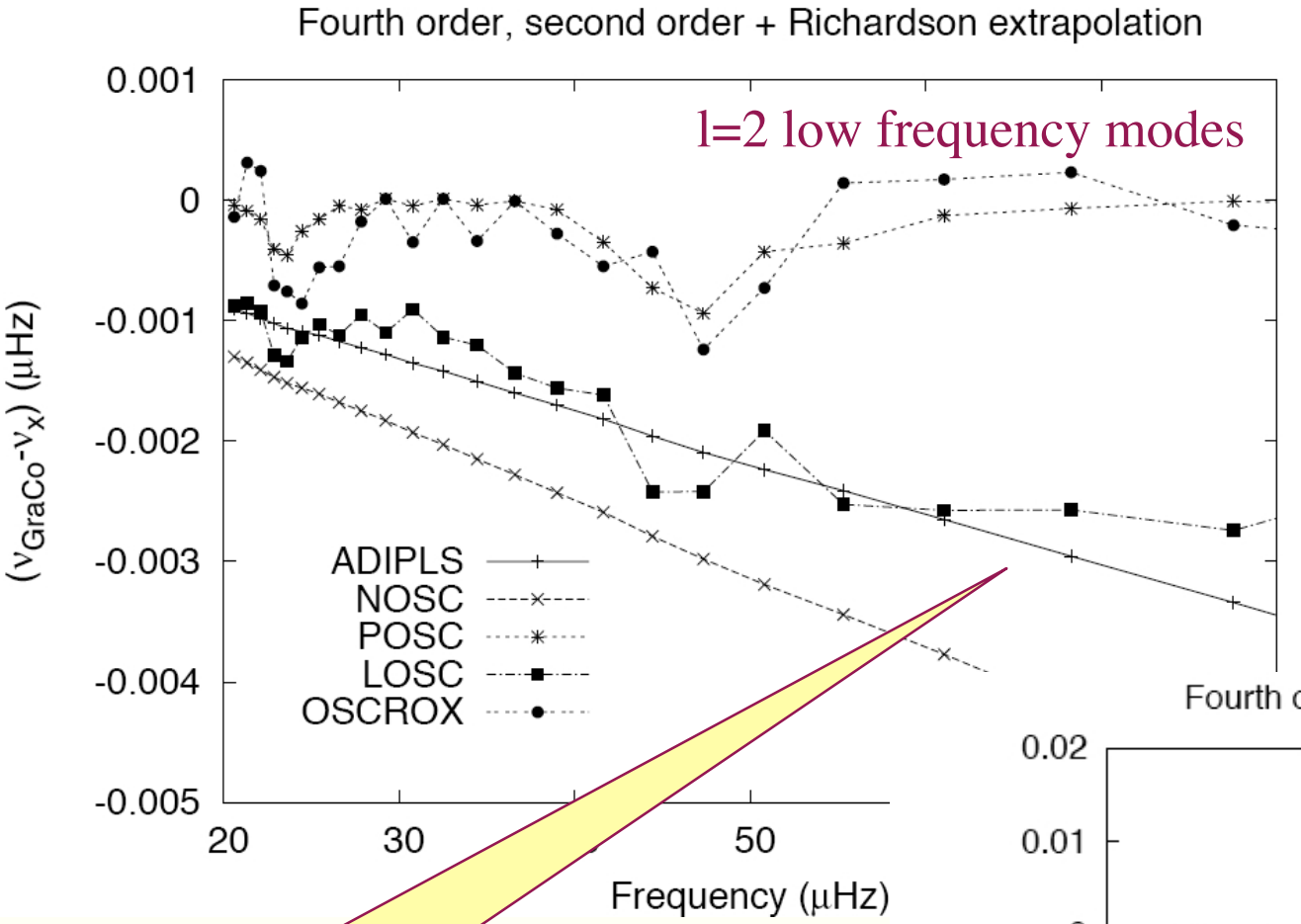
After iteration it has been possible to conclude - see Moya et al. (2007) for details - that

- the mesh of the model for calculating the frequencies is very important,
- frequency differences between codes are below 0.02 μHz (mesh 4k),
- large and small separations differ by less than the expected CoRoT errors,
- mixed modes require extra care in the mesh of the models to securer an adequate precision of the frequencies,
- the use of slightly different values of the gravitational constant introduces non-negligible frequency differences.

Further work is planned to further test the oscillation codes (Step 3 in particular).

Stay tuned and participate in you have a code!

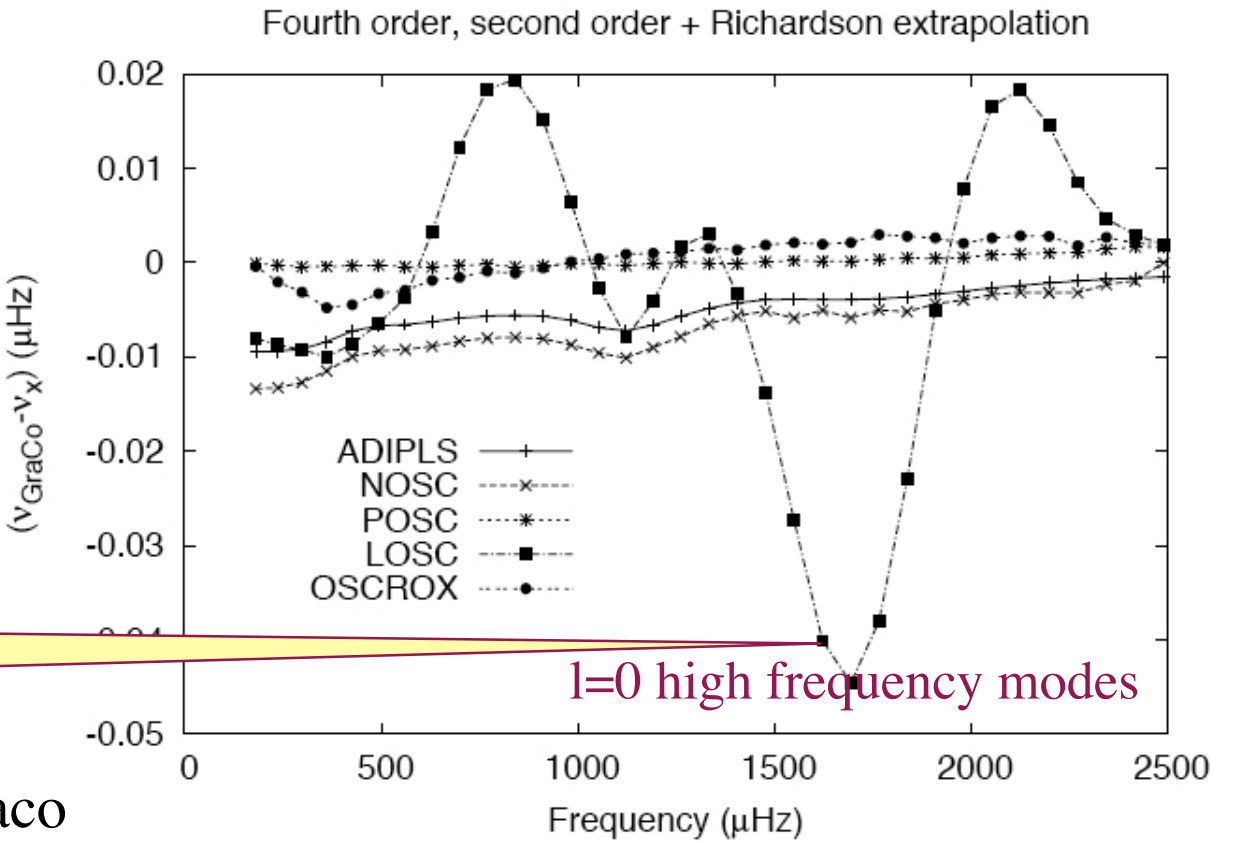
Step 1 - frequency differences



In this case the model has been provided in a mesh of 4k points. In some cases Richardson extrapolation is used for determining the frequencies.

Moya et al (2007)

Different values of G

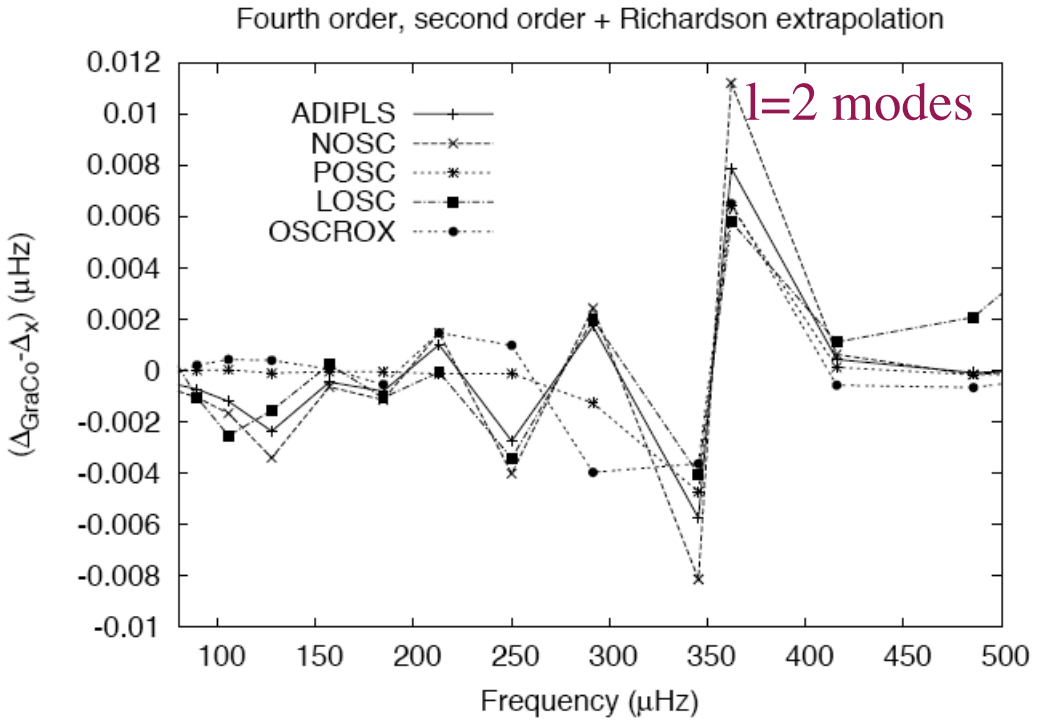


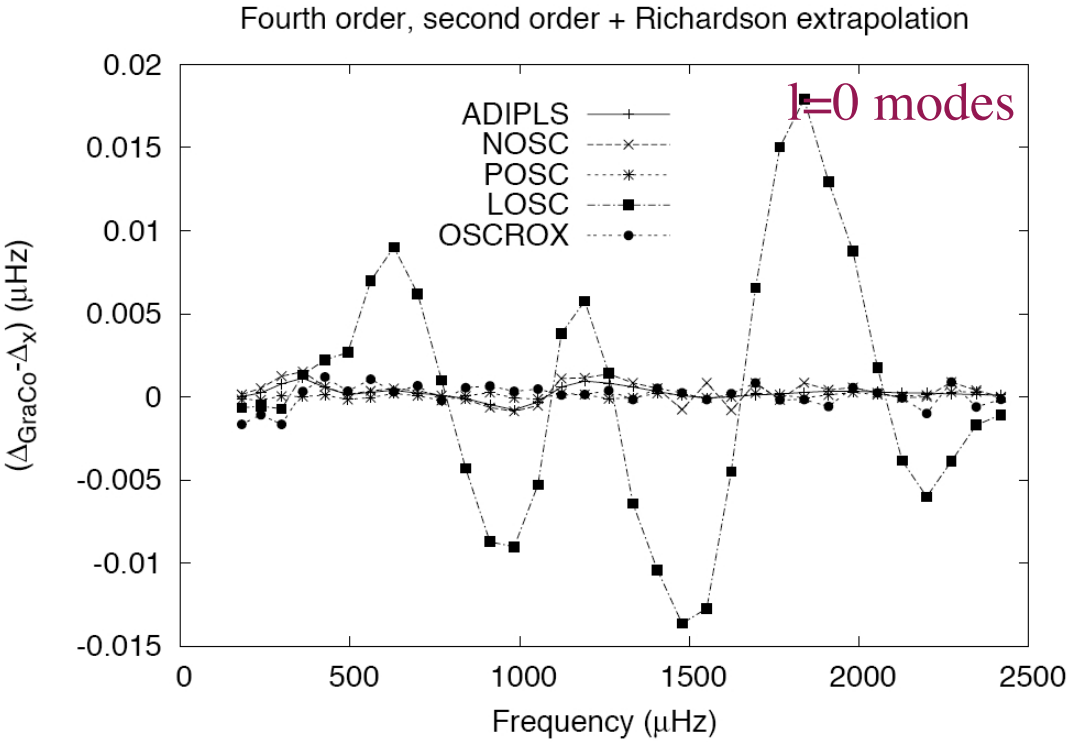
Inconsistency in the physics of the model

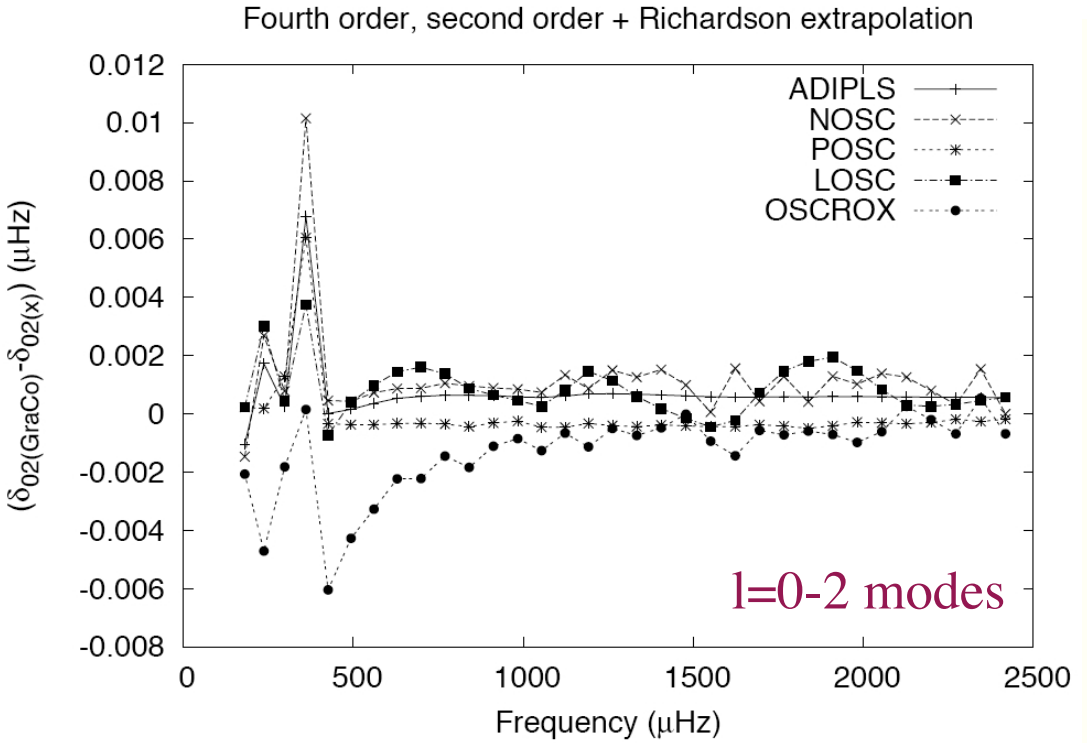
Reference: Graco

Step 1 - frequency separations

Large frequency separations.







Reference: Graco

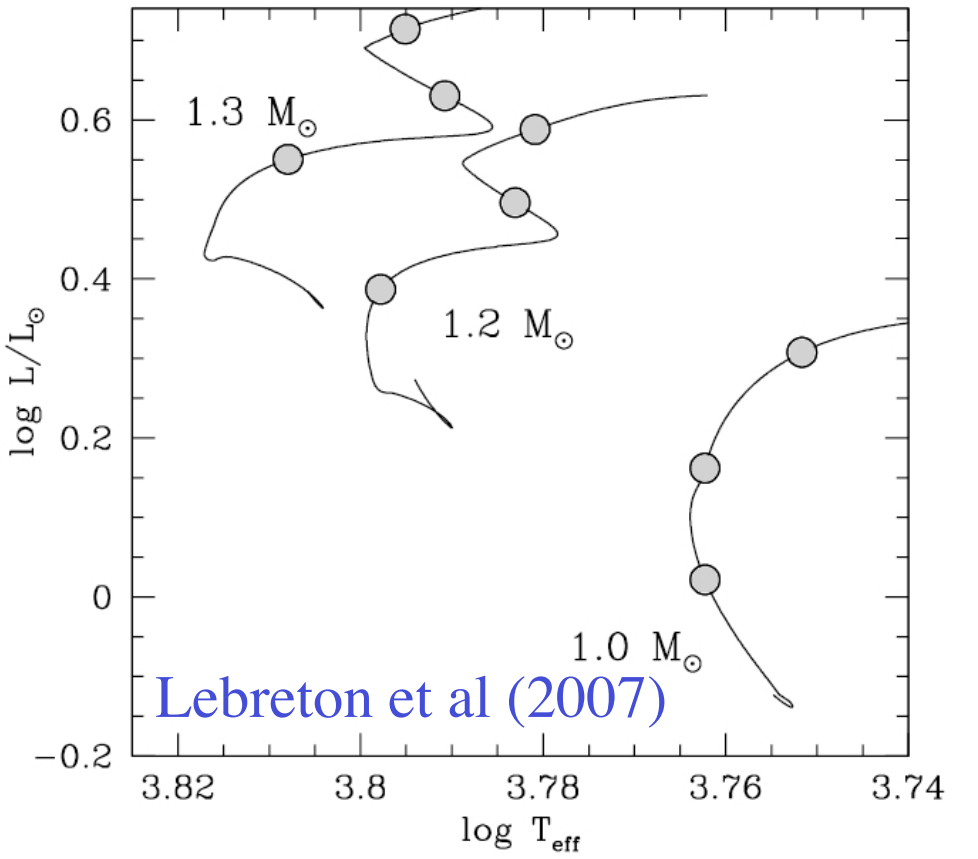
Moya et al (2007)

Small frequency separations.

Task 3 - model comparison with diffusion

The goals of this task are to test, compare and optimise **stellar evolution codes** which include **microscopic diffusion of chemical elements**.

Only diffusion from pressure, temperature and concentration gradients have been considered so far (effects of radiative forces, differential rotation and gravity waves are ignored).



Case	$M/M_\odot$	Y_0	Z_0
3.1	1.0	0.27	0.017
3.2	1.2	0.27	0.017
3.3	1.3	0.27	0.017

Phase	X_C	$M_{He,Cor}$	State
A	0.35	-	MS
D	0.01	-	TAMS
C	0.00	$0.05M_*$	PostMS

Further details are given in **Lebreton et al (2007)** and at the webpage:

www.astro.up.pt/corot/compmod/task3.html

Results (so far)

Most of the results achieved so far were in part already published in proceedings:

- Monteiro M.J.P.F.G., Lebreton Y., Montalbán J., Christensen-Dalsgaard J., Castro M., Degl'Innocenti S., Moya A., Roxburgh I.W., Scuflaire R., Baglin A., Cunha M.S., Eggenberger P., Fernandes J., Goupil M.J., Hui-Bon-Hoa A., Marconi M., Marques J.P., Michel E., Miglio A., Morel P., Pichon B., Prada Moroni P.G., Provost J., Ruoppo A., Suárez J.-C., Suran M., Teixeira T.C., 2006, **Report on the CoRoT Evolution and Seismic Tools Activity**, in **The CoRoT Mission**, (Eds) M. Fridlund, A. Baglin, J. Lochard & L. Conroy, ESA Publications Division, ESA SP-1306, 363
- (Eds) C.W. Straka, Y. Lebreton, M.J.P.F.G. Monteiro, 2007, **Stellar Evolution and Seismic Tools for Asteroseismology: Diffusive Processes in Stars and Seismic Analysis**, EAS Publications Series, Vol 26, 199 pages (19 contributions)
- Several contributions by members of the ESTA team published in the last 3 years.

A **Journal Volume (ApSS - Springer)** is almost complete for publication, including a detailed description of the work done (so far)

- evolution codes (10 articles),
- oscillation codes (up to 9 articles),
- reports on ESTA and the comparisons (up to 6 articles),
- the reference grids (up to 4 articles).

Short term plans

First: to published the journal volume!

For the near future the ESTA plans are to have specific meetings to address some of the aspects of the modelling still requiring further work, namelly:

- **On the role of convection and convective overshoot in high mass stars**

  A host has been found and the preliminary dates are in the Summer of 2008 - an announcement is expected soon...

- **On the physics of the oscillations, in particular rotation, magnetic fields and near surface effects (non-adiabaticity, excitation & damping, interaction with convection, etc)**

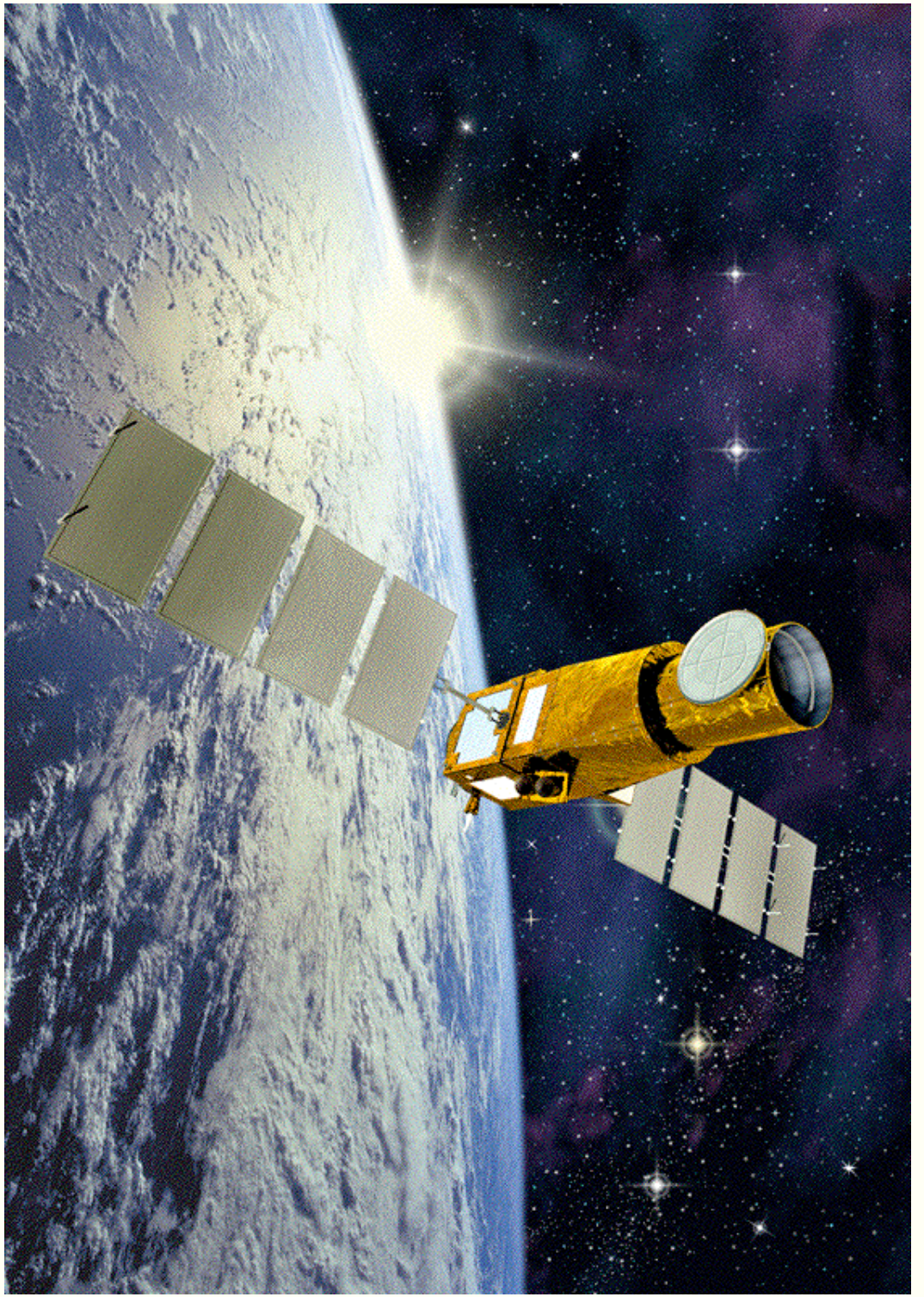
  A host has been identified - negotiations are ongoing...

Further news will be released soon!

For what needs/will be done in the medium term future come this afternoon to the:

splinter meeting on « Stellar Modelling Techniques » at 14:45

The end, for now....



Information about ESTA (data, documents, ongoing activities, results, publications, etc) is available at:

www.astro.up.pt/corot/

If you have suggestions, data, information, documents, requests, etc, relevant for ESTA please contact me at: **mjm@astro.up.pt**