Mission extension, V2

April 2009

20/05/09

1 Introduction

The mission has been working perfectly during more than 800 days, producing XXXX hours of scientific data, in 9 periods of almost uninterrupted observation (Runs).

The recent discovery of the hitherto smallest planet CoRoT-7b has demonstrated the capability of the spacecraft to discover and characterise Small Planets -- almost in the same size as the Earth and thus completely fulfills the CoRoT design criteria up to expectation. The CoRoT planet family contains a larger diversity of objects than known before

The challenge, in asteroseismology of detecting with photometry Solar Like Oscillations in solar like stars, has been achieved for the first time in a convincing way beyond any doubts. In this domain, CoRoT is really unique and will continue to be as it is, the only satellite in orbit to study the interior of many stars of all types (including bright ones).

We already have, thanks to CoRoT, a lot of interesting but puzzling results indicating a serious confict with current theoretical concepts of how these stars are working and that we need to investigate further.
More observations and sophisticated data treatment on the existing and future data will certainly reveal new ones…..

Unfortunately, in early March 2009, at the end of the 9th Run,one of the photometric chain has stopped working, and it has not yet been possible to repair it. The satellite is presently operating with only one chain, but **without any degradation of the quality of the observations**. Only the field of view and hence the number of targets in each programme is reduced by a factor two.
The same scientific objectives, valid at the beginning of the mission, can still be achieved but in an extended mission.

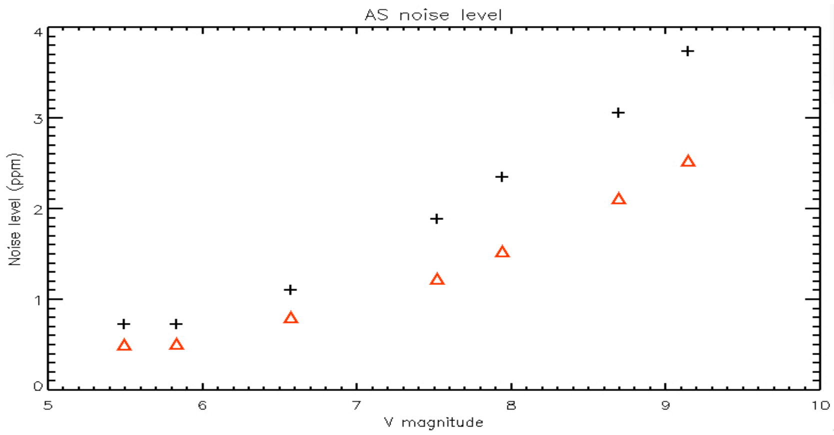
For each of its primary science goals, the scientific results, already obtained, are described briefly, highligtening a few remarkable discoveries. Then the major questions which need and can be addressed by an extended mission after this first period, are described.
The large number of scientifically promissing subjects need more than two or three years of observations, and hence request an extension of the misssion..
Priorities for the next three years are given at the end.

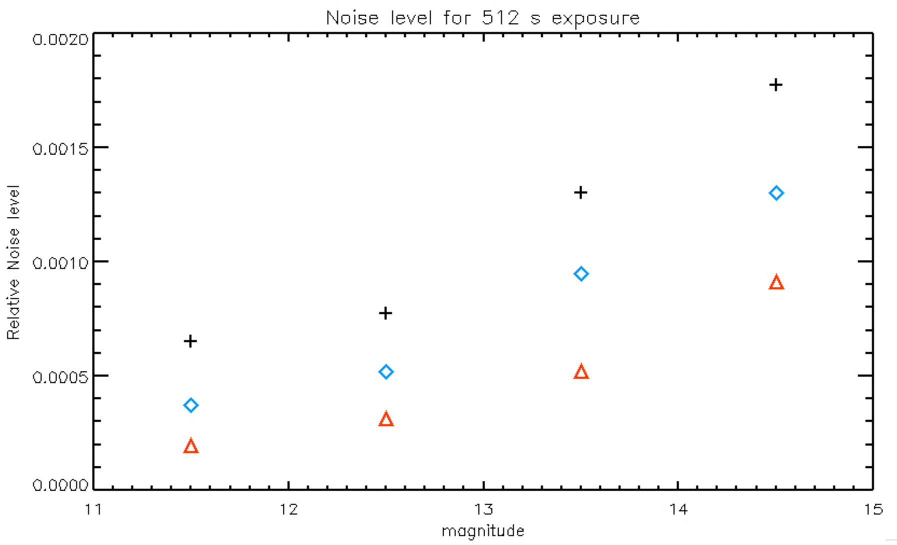
2 The performances achieved in flight

As described in details in Auvergne et al. 2009, all the scientific specifications are fulfilled.

1- The photometric accuracy, after corrections is close to the photon noise at high frequency (between 1 and 10mHz) for the seismology channel and around twice the photon noise in the exoplanet channel (in the interval 2.5 10**(-5) ,1.5 10***(-4)), as foreseen before launch.

Variation of the photometric noise as a function of magnitude in both channels.





2- The duration of the runs are also in complete agreement with the proposed programme.

Run				**Data**			**Distribution**		
Code	Number	Begins	Ends	Begins	Ends	Duration	Date	Type	Version
IRa01	3	07/01/18	07/03/04	07/01/31	07/04/02	62 days	07/12/10	astero	1.0
								exo	1.1
SRc01	4	07/04/03	07/05/09	07/04/11	07/05/09	29 days	08/04/01	astero	1.1
								exo	1.2
LRc01	5	07/05/09	07/10/15	07/05/11	07/10/15	158 days	08/02/15	astero	1.2
								exo	1.3
LRa01	6	07/10/15	08/03/03	07/10/18	08/03/03	138 days	08/07/24	astero	1.3
							08/10/29	exo	1.4
SRa01	7	08/03/03	08/03/31	08/03/04	08/03/31	28 days	08/11/06	astero	1.3
							08/09/04	exo	1.4
LRc02	8	08/03/31	08/09/08	08/04/11	08/09/07	150 days	planned 09/01/31		

SRc02	9	08/09/08	08/10/06	08/09/09	08/10/06	28 days	planned 09/04/17	
SRa02	10	08/10/06	08/11/12	08/10/08	08/11/12	36 days	seismo	planned 09/01/31
							exo	Planned 09/04/30
LRa02	11	08/11/12		08/11/13			Planned 09/06/30	

3- The duty cycle is extremely good (on average 95%) and never achieved by any mission for such long time scale.
Due to the importance of interrruption in the data for both programmes, this is a point which still needs to be treated with enormous care.

Table 1 : Duration of the runs and duty cycle

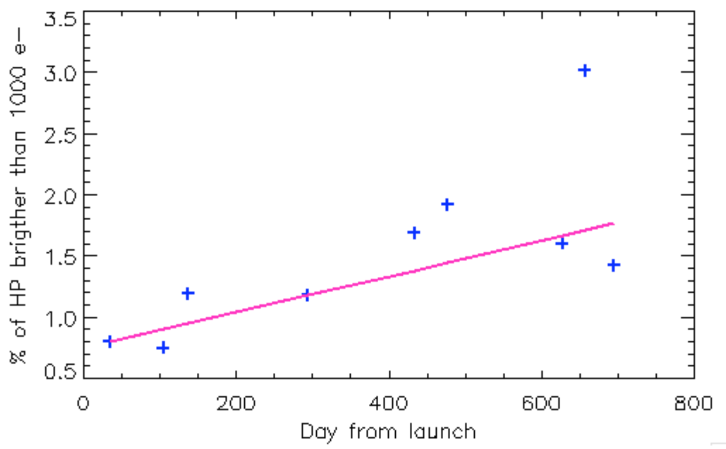
Prevision on aging.

The major surces of degradation of the preformances with time are the density of hot pixels, the decrease of the total gain of the electronic chain, the optics and the AOCS accuracy.

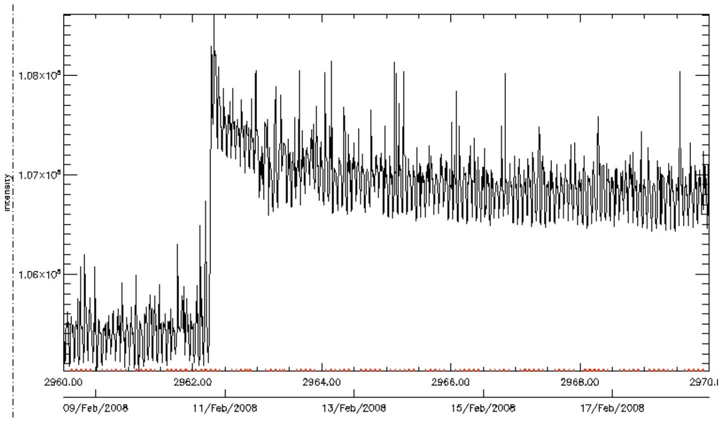
*** Hot pixels**

Along with transient events, proton impacts produce permanent hot pixels due mainly to atomic displacements in the silicon lattice. The intensity of a bright pixel is not stable in time. On short time scales (few minutes to few hours), rearrangement phase induces abrupt or an exponential decrease in the intensity. A long term annealing often follows, and a bright pixel can disappear after several days to a few years.

At the beginning of each run, the bright pixels are detected on PF CCDs images as a function of their intensity. The evolution of the number of hot pixels appears to be linear in time so that we can extrapolate this number to the satellite's end of life. The extrapolation to six years give a relative number of hot pixels of 2.5 %



Number of bright pixels measured on full frame CCD images at the beginning of each run.



Example of a background raw-data light curve (LC) perturbed by a new hot pixel appearing during the crossing of the SAA. In this example the hot pixel intensity decreases exponentially on a 1 day time scale and reaches a stable but higher mean value.

*** Decrease of the total gain of the chain**

All stars show a long term decrease in the flux that is roughly linear in time. The slope, measured on several long run for the AS and PF stars, varies linearly with the absolute flux value. Attributing the flux decrease to a gain decrease, the relative flux variation is close to 5.3 10^{-5} day $^{-1}$. The efficiency of the photons to electrons conversion will be reduced by 10% after six years in flight. This flux reduction is acceptable. If we take into account the fact that the conversion efficiency is slightly better than the specification at the beginning of the satellite life, the loss with respect the specification will be smaller than 10%.

* Optics

No significative long term PSF variation have been detected.

*AOCS

To keep a good AOCS performance, some constraints must be take into account in the choice of seismology stars on the CCD A2. We should have two stars brighter than V = 7.5 at a distance greater than 1000 pixels. With two CCD these constraints was quite easily realized.

The only performance which is significantly degraded by the loss of chain 1 is the number of targets observable in one pointing.

3 The CoRoT task Force

The exploitation of the 5 first runs has provided the material of the First CoRoT Symposium, held in Paris, Cité Internationale, February 09, under the hospice of CNES, …
More than 250 participants from 20 countries, 70 oral presentations, 130 posters.
Most of the results presented there are now being edited in a Special volume of Astronomy & Astrophysics.

In France

In the participating countries,

* In Belgium
K.U.Leuven:
Conny Aerts, Maryline Briquet, Fabien Carrier, Jonas Debosscher, Pieter Degroote, Joris De Ridder, Maarten Desmet
ROB:
Ronny Blomme, Jan Cuypers, Peter De Cat, Yves Fremat, Patricia Lampens
Université de Liège:
Kevin Belkacem, Marc-Antoine Dupret, Michael Gillon, Mélanie Godart, Andrea Miglio, Josefina Montalban, Arlette Noels, Anne Thoul

*** ESA**
Number of people presently involved in the analysis and interpretation of CoRoT Data

The total is 41 - the breakdown as supplied by the co-Is is

Aigrain	5
Kjeldsen	14
Queloz	7
Monteiro	8
Roxburgh	7

In addition to CoRoT data direct treatment and analysis, the European (+Brazilian) astronomical community has really put *huge* efforts to be able to follow-up CoRoT targets. This has taken time but is just beginning to bear fruit.
The community is prepared and expecting CoRoT's extension most eagerly.

4 The Seismology programme

A few highlights illustrate the ability of CoRoT to perform seismology measurements sufficiently accurate to allow detailed interpretations.
Then propositions for the extension are presented based on two main orientations, exploration of new types of stars and more detailed studies of some pulsators.

4.1 A few highlights

With the observations already achieved, we have proven that CoRoT has the capability to provide a completely new vision at the stars, by revealing their microvariability.
CoRoT is able to measure and characterize oscillations at the ppm level in other stars than the Sun, thus opening the way to extend helioseismology beyond the solar case. CoRoT is the first instrument to achieve it.

90 “bright” (5.4<mV<9.5) stars have been observed so far in the Seismo Field, during 4 long runs (~150d), 1 intermediate run (60d) and 4 short runs (~30d).
In seismology, all the presentations at the Symposium revealed an unprecedented step forward. CoRoT revealed low amplitude oscillations in stars looking constant so far, hundreds of oscillation frequencies where a few were detected from the ground. The characteristics of these oscillations can be followed continuously on time scales of 5 months inaccessible from the ground.

Among the results already achieved by CoRoT, a few striking ones are presented here.

Solar-like pulsation, granulation and convective core:
Corot measured solar-like oscillations and granulation in stars hotter than the Sun. This result made the cover of Science Magazine where it has been published in October 2008. Science Magazine, with Observatoire de Paris, CNES and CNRS also organized a press conference for this event at Paris Observatory (22/10/08). The amplitudes measured have been found in agreement within 25% with the theoretical values thus providing a first confirmation of these estimates at first order and a valuable guideline to refine them further. The characteristics of the granulation signature suggest time scales by 30% larger than in the Sun for convection near the surface and granule size about 4 times larger than in the Sun. The modes widths (inversely proportional to the lifetime of the modes) have been found noticeably larger than in the Sun, and than expected. This tells us that the interaction between convection and oscillation in the outer part of the stars are more efficient than expected in damping the oscillations. This also makes the data analysis more challenging and induced the development of specific techniques. In terms of stellar structure, the first seismic interpretations of the measured eigenfrequencies are addressing the crucial question of the extension of the mixing beyond the stellar convective core. This key process is responsible for the present large uncertainty on stellar age determination. These interpretations still need to be consolidated, but several studies already suggest the need for a noticeable extension of the mixed central region, of the order of the maximum expected values or even larger.

Red Giants and the future of our Sun
Toward the end of their lives, stars like the Sun expand and become giant stars. Because of the turbulent convection in their outer layers, red giants stars are expected to exhibit solar-like oscillations, but in a much lower range of frequencies (10 to 100microHz). Though some

spectroscopic observations from the ground on a few bright objects detected this behavior. the small sample plus the limitation in duration and duty cycle makes that it has not been possible to get a clear idea of how these objects pulsate.
First CoRoT data have allowed to measure clearly such oscillations in a large sample of red giants, both on bright objects in the seismo field and on faint ones in the exofield.
Beyond this, the quality of the CoRoT data has provided unambiguous evidence that both radial and nonradial modes are excited. It also confirmed the existence of modes with lifetimes of the order of a month. These results are about to be published in the review Nature (accepted).
This observational breakthrough initiated a strong effort in theoretical modelling of this stellar evolution stage. The first results suggest that it would be possible to explain the observed oscillation spectra and their variety for different stages of the structure of stars, along their expansion in the red giant phase.
It seems that the distribution of frequencies at maximum power, among all the observed red giants, presents a rather narrow peak which has to bear the print of the evolution of our galaxy. Indeed these red giants of different masses and ages are representative of all the successive generations of stars in the galaxy. The exact shape of this distribution could indeed reveal secondary peaks, indicative of different stellar populations or different stellar formation episodes, if the number of observed red giants increases. This requires long periods of observations, in the seismo field for detailed analysis of a few bright stars and in the exofield for a statistical complement.

Chimera, new types of pulsators:
Thanks to the noticeable gain in sensitivity, duration and duty cycle, CoRoT data were expected to lead to the discovery of new types of pulsating stars. HD180872 is one of them. This star was known to belong the Beta Cephei class of pulsators, young massive stars progenitors of SN-II supernovae and thus main responsible of the enrichment of the Universe in carbon and oxygen. These stars classically show oscillation periods of the order of a few hours. In the lightcurve of HD180872, CoRoT data revealed, at very low amplitude, the existence of higher frequency modes, due to stochastic oscillation, very comparable with the ones observed in the Sun. This confirms the existence of a powerful convective zone and awilla llow to scale its energetics. This discovery opens new perspective in the study of these objects where low frequency oscillations and high frequency ones could be used in a complementary way to probe the centre and the outer layers of the star. These results have been submitted to the Science Magazine and are acccepted.

4.2 Proposition for the extension

4.2.1 Cooler solar-like stars

Solar-like pulsators are the most demanding targets of the CoRoT programme, due to their so low amplitude and low coherence time. On the other hand, they are the closer to the Sun in structure and thus an important link in the extension of helioseismology to other stars. They are also a niche for CoRoT which is the first mission to be capable to measure and characterize those oscillations.
So far, 4 such stars have been observed with CoRoT: 2 'hot' (6700K) ones and 2 intermediate (6100K) ones. The hotter ones revealed spectra very different from the known solar case, apparently because of mode lifetimes shorter than expected. This fact is interesting for studying the energy exchange between oscillations and convection, but this also makes the recognition and analysis of the oscillation spectra more challenging. The two intermediate

temperature ones have been observed only recently. Their oscillation spectra look more like the solar one, but still some ambiguous features remain. In fact, it seems difficult to interpret completely this set of 4 spectra in the framework of what we know, or believe to know from the solar case, in terms of relative energy of the modes and main characteristics of the oscillation spectra. This could be due to several factors like metallicity , rotation profile, magnetic activity…It is thus important to extend further this sample of solar-like pulsators in order to disentangle the effect of the various potential parameters and have a clearer view of what is common and what is specific to these different stars. An extention by two years of the CoRoT mission constitute a unique possibility to increase significantly this sample and make it richer, especially at low temperatures, close to solar one.

RQ: This objective is among the less affected by the perspective of a reduced field of view, since bright enough solar-like targets are difficult to find targets and always principal targets (high priority targets) around which the field selection is organized. The only constraint is that for these objects, data obtained till now suggest that the length of the observations has a crucial impact on the precision of the oscillation parameters. These objects should be observed in long runs.

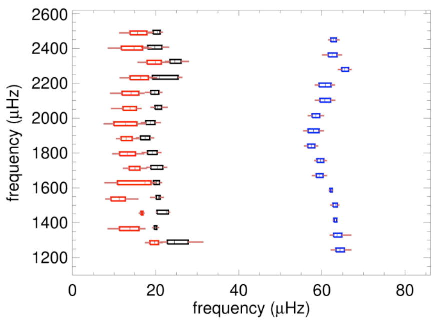
Duration of the runs and identification of the modes in solar like pusators

We have now several evidences in favor of a long duration of an observation for these types of pusators.

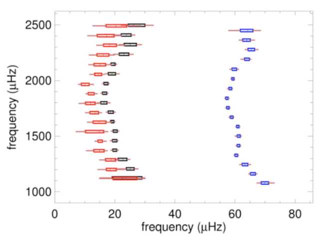
* The first one is HD 49933, which has been observed in the Initial run for 60 days and in a long run for 132 days.

The echelle diagram with the confidence box, done for the inital run only and for the two runs, illustrate the increase on the accuray on the frequencies, and then increases the confidence level of the mode identification

IRa01only



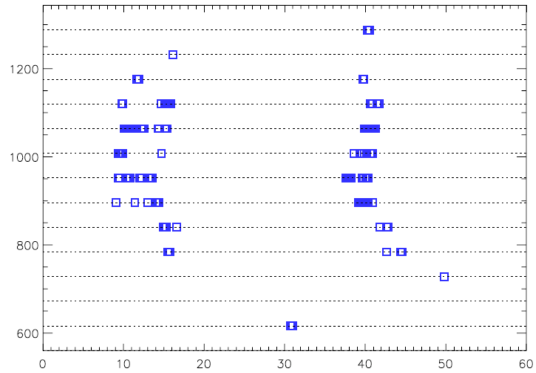
IRa01+LRa01



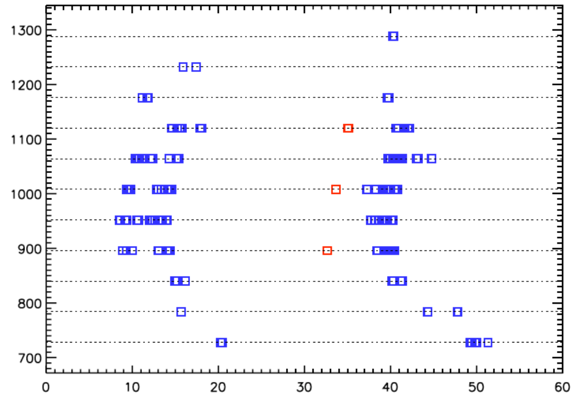
* Another example is given by HD 43589, a pulsator with higher amplitudes, in which

using the total length of the dtata, one can distinguish l=3 modes, whereas with only 80 days it is not so.

Echelle diagram for 80 days



Echelle diagram for 150 days, with modes l=3 in red



* The comparison of HD 175726 observed only 27 days with other Corot targets proves that the short observation duration is prejudicial for retrieving precise eigenfrequencies in the oscillation spectrum. We have computed the Fourier spectra of HD 49933, HD 181420 (Barban2009) and HD 181906 (Garcia2009) for a reduced 27.2-day time span. The spectra of the short time series of HD 49933 and HD 181420 exhibit the seismic signature, whereas the spectrum of HD 181906 shows no clear signal when the time series is reduced to 27 days, contrary to the full time series spectrum. As HD175726 and HD 181906 have very similar signal-to-noise ratios, we can expect that HD175726 will exhibit a spectrum as clear as the one of HD 181906, if observed during a Corot long run.
As compared to other CoRoT targets, HD175726 is cooler, with an estimated G0 type. Reobserving it will permit to extend the CoRoT seismic analysis to G dwarfs.

Table 3. Contributions to the power density at the frequency where the seismic signal is maximum, and mean seismic signal-to-noise ratio for HD 175726, compared to other CoRoT targets. *Indication of the maximum height-to-background ratios for HD 175726, in the spectrum respectively rebinned to 1 or 2μHz.*

star	$f_{\max}$ (mHz)	mean power density at maximum: total	granulation	noise	p modes	$\langle$SNR$\rangle$	HBR$_{1\mu\mathrm{Hz}}$	HBR$_{2\mu\mathrm{Hz}}$
		.... (ppm^2 μHz^{-1})						
HD 49933	1.8	0.44	0.11	0.14	0.19	1.18		
HD 181420	1.6	0.65	0.20	0.28	0.17	0.79		
HD 181906	1.8	1.01	0.10	0.79	0.12	0.39		
HD 176725	2.0	0.41	0.05	0.31	0.05	0.37	4	3

Other candidates exist in the CoRoT eyes, and the next Long run in the anticenter direction, as already prgrammed will focus on such a star HD 43587.

4.2.2 B supergiants

The internal structure of B supergiants is closely related to their past history of core hydrogen burning. For such massive stars (M > 10 Ms), the convective core in which hydrogen burns, is surrounded by a semiconvective region whose structure is not understood at present. If a partial mixing takes place, the adiabatic and the radiative gradients are so close during the whole main sequence phase that the ignition of the hydrogen shell burning at the onset of the supergiant phase gives rise to a fully convective zone (ICZ). *The existence of an ICZ is very important because it is the necessary condition to allow excited g-modes in the spectrum of a B supergiant.* The presence and the extent of the ICZ closely depend on the treatment of semiconvection but also on the amount of rotation and mass loss. The conclusion is that the observation of g-modes (even only one g-mode!) in the spectrum of a B supergiant is a signature of the physical processes which have been at work in shaping the layers surrounding the convective core during the main sequence phase. These layers play a significant role in the location in the HR diagram and the duration of the more advanced phases of evolution which in turn affects the ratio of blue/red supergiants. *No B supergiants have been selected as main asterosismology targets during the first three years of the CoRoT mission which means that a large zone of the HR diagram is still fully uncovered by CoRoT.*

This programme can be achieved through the observation of a few candidate targets in the anticenter direction, of several months duration

4.2.3 Clusters (W. W)

Members of Open Clusters were born at about the same time, from the same molecular cloud and therefore have similar chemical composition, if the cloud was homogeneous, and members usually have similar ages. Equally important, the distance of a member can be estimated from cluster properties without knowing a parallax. Open clusters allow therefore to test models of stellar structure and evolution in a much more stringent way than is possible with an isolated star.

Within its field of view of ~1.3 square degrees, COROT is most suitable for observing also nearby clusters, which allows for complementary measurements (e.g., spectroscopy) without the need of heavily oversubscribed 8m-plus telescopes. In the foreseeable future COROT will be the only space telescope capable to observe young clusters. Although the open field of the MOST satellite is of comparable size, the limiting magnitude for MOST is around V = 12mag, which constrains the list of observable clusters significantly. Furthermore, COROT features a more than 7-times larger aperture, considerably reduced background and hence provides much better photometric accuracy. The KEPLER field-of-view on the other hand is located high above the galactic plane where no young clusters can be found. Hence, the KEPLER mission is not suited for such objects.

Several open clusters are visible in the current eyes of COROT: 14+/-3 in the center direction and 41+/-4 in the anticenter direction. The actual number depends on the requested level of population in the color-magnitude diagram and how much stray light can be tolerated close to the borders of the "eyes". Five of the clusters in the anticenter direction are younger than 10 million years allowing thus to observe stars that were recently born, still contract towards the main sequence and have not yet started hydrogen burning. Among those are the two clusters that were already observed by COROT with much success: Dolidze 25, which was observed

as additional target during one of the long runs, and NGC 2264, which was driving the selection of a short run (SRa01).
This later run also illustrates the breadth of science which can be addressed with open clusters. The "NGC 2264 team" consists of ~70 scientists from the COROT community which study the interaction of young stellar objects with their circumstellar matter, investigate the rotation and activity properties of cluster members, probe the interiors of pre-main sequence stars using asteroseismology and search for planetary and stellar eclipses around young stars.

4.2.4 A/F stars:

The observations of A/F stars in and around the instability strip of delta Scuti stars has been an intense activity from the ground for decades. This domain of masses just above the solar-like pulsators is dominated in terms of energy production by the CNO cycle and not the PP chain as in the Sun. Consequently, this is also the domain where the outer convective zone becomes very shallow and the convective core becomes the dominant feature in the stellar structure. This domain is characterized by the very rich variety of stars classes showing specific surface chemical composition, specific pulsational behaviours, specific rotation rates (delta Scuti stars, Gamma Dor CP stars, HgMn stars, Am stars…). This rich variety is the indication of how transport of chemical species and transport of angular momentum develop and interact in intermediate mass stars on Main Sequence, one of the present high priority open question in stellar physics. In this domain, CoRoT has brought in two years a wealth of data of unprecedented quality, revealing hundreds of oscillation modes where only a few tens could be found from the ground. It thus becomes possible, for the first time, to address the long-standing problem of the amplitude distribution between modes, that is to say the energetic aspect of the oscillations and the processes ruling it.
CoRoT also revealed stars showing no oscillation at the ppm level. The occurrence in the instability strip of such stars, in which helium responsible for triggering the oscillations would have sunk and the link between this and rotation is also a long standing question and CoRoT by lowering the detection level by a few hundreds shed a new light on it. After two years of the CoRoT programme, we have observed about 40 of those objects, half of them in long runs. Even if this number is high, it has to be increased again, as the number of processes at stake is also large, as attested by the variety of behaviours of the variability in this domain. The extention of the CoRoT mission by two years would allow to increase this sample and help to investigate further which differences in structure exist between these different types of objects and distentangle the effects of the global parameters (rotation, metallicity,...) responsible for it.

RQ: This objective is of course sensitive to the perspective of a reduced field of view, since the number of targets stars observed simultaneously will be divided by 2. However, the data already obtained have confirmed that CoRoT is doing well on such targets up to mV=9.5. They have also shown that for such targets, valuable data can be obtained also in intermediate or short runs, down to a few weeks. They also showed that, at this magnitude, A/F type stars are generally easy to find as secondary targets in selected fields, thus adding only light constraint on the field selection. For these stars, the reduction of the field of view can thus be compensated by the prolongation of the observations.

4.2.5 O stars

The evolution of massive O stars is very important since they are the progenitors of supernovae. They suffer a rather large amount of mass loss during core hydrogen burning and an even greater one once they leave the main sequence. This transforms O stars into Wolf-Rayet stars. The origin of this drastic increase of mass loss is still unknown. A possible explanation could be that they are subject to high amplitude pulsations coming from the excitation of "strange modes". The trapping of such modes requires a particular internal structure with a cavity where the density *increases* towards the surface. This can only happen if the radiation pressure is very large, i.e. in stars with a very high mass/luminosity ratio. Asteroseismology will in this respect be an invaluable tool to constrain this mass loss which in turn will precise the WR/O stars ratios and eventually the type II/type Ia supernova ratio. Some ground-based observations suggest that such modes could indeed exist in at least one O star. It would be extremely interesting to select O stars in the sismo field to help understanding the mechanism leading from O stars to Wolf-Rayet stars and then to supernovae. *O stars have been observed by CoRoT in one short run only, which means that there is an urgent need to go further in this exciting domain.*

4.2.6 Reobservation of Be stars

Some fields contain very active Be stars, particularly LRa1 with HD 49330 in the sismo field. The Corot light curve for this Be star has allowed us to discover many frequencies with associated amplitudes varying along the run; dominant frequencies detected during the outburst are different from the ones detected before and after the outburst. A wider temporal coverage will teach us about the stability of main frequencies and their role in the triggering of outbursts, which are known to be recurrent.

5 The Exoplanet hunting programme

5.1 The present CoRoT findings

5.1.1 The striking discoveries

CoRoT has detected planets that hadn't been discovered so far by other transit surveys. Basically this is because transit search is less biased in photometry from space than in spectroscopy from the ground.
In particular at short (very short) periods and particularly around active stars transiting planets are very difficult to detect by the ground-based surveys : (i) giant planets are frequently missed, (ii) small planets are undetectable.
So, the method is complementary to the ground based ones and extends the characteristics of the discoverable planets.

At the time of writing, there are more than 350 transiting events detected by CoRoT. About 25% have been observed with complementary techniques, and 7 planets are fully confirmed and characterized. A number of unsolved cases remain, either due to a difficult spectroscopic follow-up (fast rotators, active stars) or to unsufficient observing material for a robust conclusion.

Table 2 gives the parameters of the first CoRoT planets and some of their main characterisics. Most of the CoRoT planets are in the domain of giant gaseous planets, with radii ranging from 0.97 to 1.49 R_{Jup}. The two most inflated ones (CoRoT-1b and CoRoT-2b) also correspond to very short periods (1.51 and 1.74 days respectively), confirming the role of irradiation in the radius evolution.
CoRoT-4b et CoRoT-6b are among the rare transiting planets with orbital period greater than 4 days. Thanks to the analysis of their CoRoT light curve the stellar rotation period has been measured photometrically and show that both systems are synchronised. Among other interesting pecularities, while the radial velocity surveys have shown that planetary frequency is rising as a function of the metallicity of the host star, 3 out of the five CoRoT hot-Jupiter are surprisingly metal poor.

CoRoT has also started to widen the domain of planet mass : from the very massive CoRoT-3b (21.6 M_{Jup}), to CoRoT-7b, first planet in the telluric size domain for which radius and mass have been measured.

Table 2 : The confirmed planets

Name	Period (day)	Mass (M_{Jup})	Radius (R_{Jup})	Density (g/cm^3)	Star type	Main features
CoRoT-1b	1.51	1.03	1.49	0.38	G0V	planet radius Metal poor host star
CoRoT-2b	1.74	3.31	1.46	1.31	G7V	Active star – planet radius
CoRoT-3b	4.26	21.6	1.0	26.4	F3V	Brown dwarf or Super planet
CoRoT-4b	9.202	0.72	1.19	0.525	F9V	long orbital period Synchronized system
CoRoT-5b	4.03	0.46	1.39	0.217	F9V	Very low density
CoRoT-6b	8.89	2.96	1.15	1.94	F9V	Low metal content

CoRoT-7b	0.85	1.4 – 1.9 10^{-2}	0.157	4.23	G9V	First telluric planet with mass and radius measured

5.1.2 A difficult and lengthy confirmation process

We stress out that the CoRoT Exoplanet science team has decided to publish confirmed and fully characterized planets only and not simple planet candidates list. To achieve such a goal, a complexe strategy of tests has been set up, well beyond the simple detection of transits in the corot light curves. As several configurations due to stellar eclipsing systems, might indeed result in events mimicking true planetary transits number of verifications are mandatory to rule out reject transiting stellar companions.
The regular temporal coverage over a long period of time and the good photometric precision that CoRoT provides is a much favorable configuration compared to ground-based surveys and allows the best possible information to be extracted from the light curve, mainly with search for secondary transits and out-of-eclipse ellipsoidal variations. It allows to rule out about ¾ of the candidates.
For the remaining candidates, complementary ground-based observations are essential. They help to identify and discard the remaining stellar eclipsing systems.
Complementary observations are also mandatory to get a complete characterization of a planet. The planet mass could indeed be measured only by radial velocity observations. Combined to the planet radius, it gives the planetary mean density, providing thus fundamental insights into their interiors.

The publication reporting the discovery of CoRoT-7b is a very good example of the complexity of the sequence of tests needed to assess a robust level of confidence in the identification of the nature of the transiting object. It has been possible to rule out with a very high probability all the impostors without the radial velocity test. And this was fortunate as for such a system of very small mass the signal is very small and embeeded in the variability due to activity. HARPS has succeeded to confirm the planet and measure its mass but it costed more than 100 nights of this 3.6 meter telescope equipped with a presently unique spectrograph.

However, to get absolute planetary masses and radii, reliable estimates of the mass and radius of the parent star is a critical issue and the magnitude range of the CoRoT/Exoplanet targets, this could be achieve only thanks to spectrocopic analysis. At last, complementary observations allow to perform deeper studies of the planet properties, such as for exemple, the measures of the spin-orbit alignement which provides some insights on the planetary system history. This adopted strategy clearly increases the scientific return of the CoRoT mission.
The list of confirmed planets will increase as there are still many candidates awaiting for a confirmation by ground based complementary observations.

5.1.3 New questions raised by CoRoT

All these objects can convey important informations for the models of planet formation each asking a specific question: (i) why CoRoT-1b orbit a metal poor star discarding from the general tendency of the planets to form around metal-rich stars (a correlation that is thought to support the core-accretion scenario), (ii) what is the link between the existence of a close in planet and the activity of the parent star, and when do the two body start a mutual history (iii) what is the difference between the formation of a brown dwarf and a planet, (iv) is CoRoT-7b a rocky planet formed like a Terrestrial by gradual accumulation of planetesimals or the remnant core of a planet formed like gas (or icy) giant stripped from its gaseous layers.

The detection of a planet like CoRoT-7b around an active star has clearly stated the capability of CoRoT inside the international competition. This planet could not have been detected from the ground neither with a transit survey nor with the best spectrograph presently available. This has to be taken into account to set up the niche where CoRoT will have the best chance to impact exoplanetary science.

5.2 The challenge of the Small Planets

CoRoT could help to answer an important question : does a family of very small (rocky) planets like CoRoT-7b exist or not at very short periods and are associated with other more massive planetary companions.
To confirm/invalidate the existence of such a planet family will put important constraints on the models of planet formation.

5.2.1 Small planets very close to their star

We already had some success in this field with the smallest candidates ever found by the transit method. A companion planet with Neptune size was, then, discovered by HARPS, showing that CoRoT is able to detect small planets around solar type stars, measure their radius and measure their mass.
Finding close-in system is not a surprise since others have been discovered already (a few dozen of close-in systems were also announced by the HARPS team) and can be easily explained by the migration models.
However, what is crucial in the CoRoT discovery is that one of the companion is a rocky planet. A very recent paper by Mayor et al. (2009) reports the discovery of another close-in system containing a rocky planet around an M star.
As a result, we can reasonnably expect that other similar systems, composed of a rocky terrestrial planets associated to a giant planet, should exist.
Such close-in systems are well within the grasp of CoRoT for three reasons :

(i) the high transit number,
(ii) the high geometrical probability of detection (> 30% in the case of CoRoT-7b),
(iii) the higher transit probability for a system than for a single planet.

The discovery of this small planet also clearly confirms that CoRoT is well optimized for the detection of planets in the very close proximity of their stars. Since close-in planet systems seem to be the rule, CoRoT could have (before KEPLER) the unique opportunity to bring relevant statistical results on these systems covering the planet size spectrum from giants to super-Earths and the range of period from 1 to 20 days (approximately).

5.2.2 Small planets at long period

Presently no long-period transiting planet was found in the low mass range of the mass spectrum. The discovery of one (or some) small long period planet(s) is a challenge that can be an important step for the future missions. Improving the detection of these planets is possible by increasing the length of the observation.

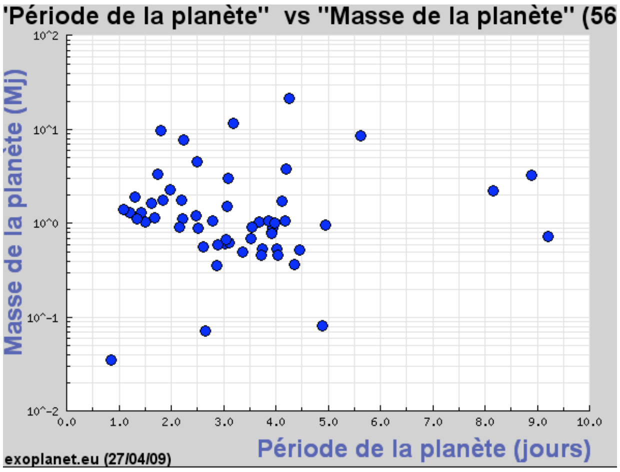


Figure x: The transiting planets at periods less than 10 days. The number of planets is very small in the low mass range. There is only one planet above 20 days, and a good CoRoT candidate at more than 100 days.

5.3 CoRoT and Hot Jupiters

Here the goal is mainly to enlarge the population of the planet family accessible from the ground and also to enrich them with peculiar objects or with planets in systems or in long period orbits.

5.3.1 Increasing the sample

While the number of transiting planets is increasing, thanks to intensive observational effort carried from the ground for years, this population displays an unexpected puzzling diversity. Clearly, the orbital and mass distribution properties the ground surveys are exploring is by far still too limited. Efforts should be put to increase the sample, and mainly, to broaden the observed parameter space.

CoRoT has demonstrated its abilitiy to widen the range of the orbital periods and explore the transiting population at longer orbital periods, a domain which remains nearly unexplored for the transiting planets.

A number of the planets discovered by CoRoT are very peculiar either by their size or mass, but also by the metallicity, activity or rotation of their parent star.

It is very important to found other planets like CoRoT discovered so far, even if there are big ones. Indeed, all of them are so different from the ones discovered from the ground that they bring significant clues for understanding better the physics of the giant planets and the way they form.

5.3.2 Secondary eclipses and planetary atmosphere

The transiting planets are indeed the only ones for which the nature, internal structure, and atmospheric properties can be probed. This has a strong impact not only on our understanding of their interiors and their formation mechanisms but also on the physics of their atmospheres. This could be achieved by deeper complementary analyses carried out on the CoRoT light curves themselves but also thanks to ground-based complementary observations.

Depending on the composition of their atmosphere, the highly irradiated close-in giant planets are valuable targets to probe their atmospheric properties. Fortney et al. (2008) proposed the existence of 2 classes of hot Jupiters, each being expected to have very different emitted spectra and day to nightside circulation. As a consequence, the depth of the secondary eclipse which corresponds to the occultation of the planet by its host star, is expected to be significantly different from the one class to the other. The detection and measure of the secondary eclipses is thus a critical observational test and provides precious information about their atmospheric properties.
Studies carried out thanks to the The Spitzer Space Telescope, in the near infrared spectral domain where the planet thermal emission is more important, have produced number of detections in good agreeement with the model predictions. However, in the optical domain, the expected signal from the secondary eclipses is expected to be around some hundredths of a percent and remain impossible from the ground. Despite several attemps, no positive detection from the ground has been reported so far. However, such measurements in the optical domain would nicely complement the Spitzer measurements. They would allow for an independent test of the theory of Fortney et al. and would made possible a detailed modeling of the highly irradiated hot Jupiter.
Very recently CoRoT has demonstrated its unique capability with the detection by two independant studies of the secondary eclipses of CoRoT-1b (Alonso et al., 2009 ; Snellen et al., 2009). These first results and the improving quality of the data reduction pipeline with better the correction of jtter shows that such studies could be carry out over an increasing sample of planet in the post –cryogenic Spitzer area. It demonstrates that **CoRoT could have a significant contribution for the study of exoplanetary atmospheres**.

5.3.3 Transit time variations and multiple planetary systems

The high quality of the CoRoT photometric measurements can be used to investigate the presence of other planets in the same system, thanks to the analysis of the transit timing variations which need long term monitoring and a high time sampling . Depending on its mass and orbit, the presence of an additional companion could indeed perturb the orbit of the transiting planet and cause deviation from strict periodicity of the observed transits with sensitivity to very small masses (Earth masses or below).

In general, Transit Timing Variations (TTV) caused by a companion planet have, for reasonable values of the planet parameters, amplitudes of the order seconds (e.g. Schneider 2002). But there are two exceptions: resonant planets where the TTV can be of the order of minutes (Nesvorny and 2008) and Trojan planets where it can be of the order of tens of minutes (Schneider 2008).
TTVs are larger in long period planets because they are proportional to the star-planet distance if due to a second planet. TTVs due to a second planet also increase with time if they are due to a distant planet. Reobserving the same field after a couple of years thus increases the likelihood of TTVs. Finally, TTVs due to an exo-moon are more likely at large distances (moon around hot Jupiters are not very likely).

Moreover, the lack of detected transit time variations allows to place limits on the mass and orbital properties of an hypothetical additional planet.
Two recent independant studies carried out on CoRoT-1b detected no periodic period variation at a shorter period than the duration of the CoROT observational window (55 days). They also demonstrated that **CoRoT has the sensitivity to detect or rule out planets with masses greater than that of Mars in the 2 :1 outer mean motion resonance, providing insights into the planetary system structures and further their formation and evolution**.

5.3.4 Systems of transiting planets

New evidence suggests that planetary systems are the rule at low mass:

- the bimodal theoretical planetary initial mass function points to an abundant population of Hot Neptunes with the two peaks being even narrower for radii and near Jupiter and Neptune-values.
- new dynamical stability investigations demonstrate the physical possibility of ultra-dense close in planet systems (10 or more planets in the period range of 1 to 10 days in the same system);
- radial velocity discoveries published in spring 2008 show a 30% presence of planets with Msini of 5 to 30 earth masses around solar like stars. All in systems.

Systems with two transiting planets would be an extremely interesting configuration to characterize at best the two planets.

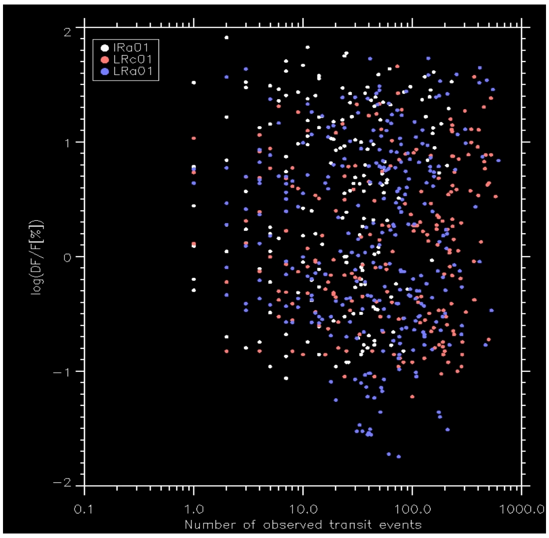


Fig. y : Depth of all the transit signals detected in the three first field of view observed by CoRoT as a function of the transit number.

5.4 Reobservation of previous candidates

In the field of view already observed by CoRoT a number of candidates have received less attention due to the small transit number in their light curve. For many others, follow-up has become very difficult due to the imprecision in their ephemeris (which makes the predictions for their transit times increasingly unreliable).

5.4.1 Revisit two-transits candidates

These targets are extremely interesting because they correspond to long period planets. The longest period transiting planet presently known (HD 17156 b) has a period of 21.2 d corresponding to a = 0.16 AU, still a hot planet. Longer periods correspond to cool planets with a different physics and mass-radius relation.

Presently for the runs LRc01 and LRa01 there are 4 long period candidates with transits each with depth ~1% and periods from 50 to 80 days corresponding to a~ 0.3 AU (for the other long runs). Were they planets, this number would be consistent in order of magnitude with the statistics of ~ 1% of planets in the a = 0.15 – 0.5 region from RV surveys.

The reobservation of the same targets preferably in another long run should give transits with a probability 100% and would confirm the period.

5.4.2 Recovery of lost ephemeris

For many of the candidates identified in the CoRoT light curves the follow-up turned out to be very difficult; this is due to the imprecision in their ephemeris which makes the predictions for their transit times increasingly unreliable.
This was the case for candidates from the first short runs SRa01 and SRc01 (four priority 1 candidates + six priority 2 candidates). Considering that Short-runs are nearly as effective as longer runs in detecting Hot Giant planets, one may estimate that we are loosing some 2-4 real planets among these priority 1 and 2 candidates, unless something is done about it.
To recover these candidates' ephemeris from ground-based observations is very uncertain and should be done one by one for each candidate. The only efficient solution would be a re-observation of the short-run fields. The sooner would be the better, due to the increasing uncertainty of the transit times:
- For SRa01 a one-week run would recover transit-times by all good candidates, including the promising SRa01_E1_0770 with a period of 6.7days
- For SRc01, a minimum of a 3-day run would also recover all priority 1 and 2 candidates (except one of priority 2 with a 21d period); in order to also recover most of the numerous candidates of priority 3, a 1-week run is also proposed.

5.4.3 Increase the significance of the transit signals

At a given photometric accuracy to increase the significance of successive transits, is possible by increasing the length of the light curve. For example, if the data set is two times longer, the SNR would be approximately increased by a factor 1.4 . Transits marginaly detected with a SNR of 3 would become more secure candidates with a SNR of 4.2.
A number of undetected transit signals could become marginally detected candidates, increasing slightly the possibilities of new discoveries; this would be highly valuable in the case of small long period planets.

5.5 The strategy for exoplanet search

The different objectives presented before point towards two different observing programmes: one oriented towards an increase of the runs, the other one towards a reobservation of preceeding fields.

5.5.1 Optimum duration of a run

Increasing the number of the runs is required by the detection of small close-in planets, to detect multiple systems, and to increase the sample of hot Jupiters,

To find small planets at long periods, the strategy is to re-observe fields and targets that were already observed during another long run. This would help to confirm/invalidate a number of candidates. For all the light curves this would increase the SNR by a factor 1.4. Transits marginaly detected with a SNR of 3 would become more secure candidates with a SNR of 4.2.

The impact on the detection of a reduction of the run duration has been analyzed in a more quantitative way using all the detections made during the long run, LRc01. The change of the performance as a function of the run duration is reported in Figures 1 and 2, below. It is found that the number of detections is reduced by only 10% when the duration of the run is divided by 2.

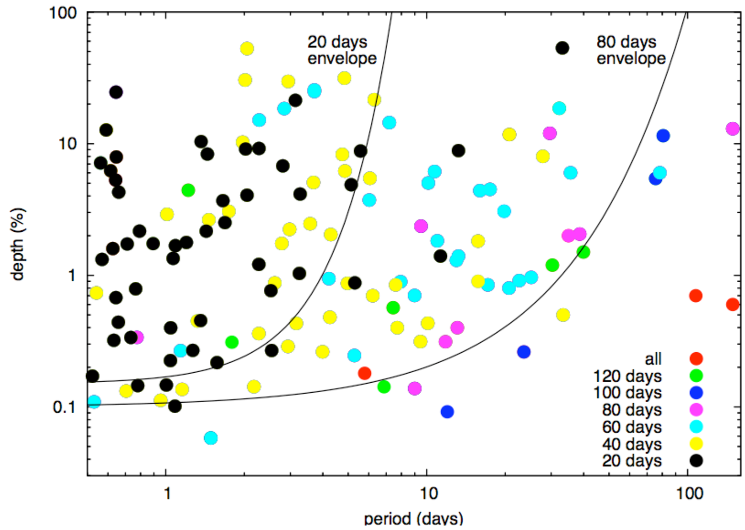


Fig. xx : Depth of the transit candidates detected by the CoRoT detection teams in the run LRc01, as a function of the period of the signals. The various colors indicate the length of the light curves on which the candidates were detected. A run with a duration of 80 days do not change significantly the detection capacity at the various periods.

Fig. yy : Total fraction of the detected candidates as a function of the length of the run LRc01. The various dots correspond to the different durations of the run. For a mid run of 80 days the loss fraction is only ~ 6% of the number of candidates detected after 153 days.

5.5.2 Bright stars

Up to now the planets discovered by CoRoT were found around targets brigther than mV~ 14; CoRoT-7b was discovered around a 11.7 magnitude star.
Of course, for these targets we have stronger signal and less contaminationby the background stars. The follow up operations are easier and permit a complete characterization; complementary studies are also easier like detection of secondary transits or TTVs (additional arguments should be found in the Plato science case ...).

To increase the total number of bright stars can be done only by increasing the total number of runs.

5.5.3 Towards an observing programme

So, on the exoplanet side the issue is to manage (i) the necessity to increase the statistics (in order constraint the formation models) with (ii) the challenge to explore the planet size spectrum toward the small scales.
Basically, widening the statistics requires to give priority to the number of the monitored stars whereas to get a better significance requires to give priority to the length of the observations. So, two possibilities have been investigated: (a) to have mid-runs that last ~ 75 days instead of the nominal duration of 150 days, (b) to re-observe the same fields and stars after a 6

month delay. The probability of detection is increased (decreased) by a factor of ~2 and the SNR is decreased (increased) by a factor 1.4 in case (a) ((b)), respectively.

5.5.4 Strategy

In summary, for the exoplanets, the goal could be to focus on the detection of the small planet systems (super-Earths and Neptune like planets) that should be present in the very close vicinity of their parent star. This could also offer the possibility to detect a few systems of transiting planets. The optimal strategy to reach this goal would be to have runs of observation with durations of the order of 75-80 days.

6 A program for 3 years

7 References

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