Comm. in Asteroseismology
Vol. 150, 2007

The PLATO mission concept

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Abstract

PLATO is a project for a future space mission that is intended to be submitted in response to the upcoming ESA "Cosmic Vision" announcement of opportunity. The science goal of PLATO is to provide a solid observational basis to understand the formation and evolution of stars and their planetary systems. This goal will be achieved by determining statistically the distribution of sizes and orbits of exoplanets, down to sub-earth sized planets and up to orbits at several AU, and the properties of their parent stars through asteroseismology.

The observational concept of PLATO is based on ultra-high precision photometry from space. The strategy is to identify a sample of more than 100 000 bright stars, and to perform on all of them a long-term high precision monitoring in white-light visible photometry. This monitoring will be used on one hand to search for and characterize planetary transits in front of these stars, and on the other hand to detect and analyse oscillations of the same stars and thus probe their internal structure and dynamics.

The requirements for such a mission are challenging: a very wide field-of-view, near 900 square degrees, as well as a large effective collecting area, of the order of 1 m^2, are necessary to monitor simultaneously a sufficiently large sample of bright stars, with a sufficient photometric precision. The duration of the monitoring must be of at least 5 years.

We present an example of instrumental concept compliant with these requirements. It involves a large number of small pupil optics, each one illuminating its own large format focal plane. Although challenging, this concept builds on heritage from previous missions and previous studies, and presents a low technological risk.

Detailed industrial studies of the proposed mission are currently being undertaken by Astrium and by Alcatel/Alenia, and the final form of the mission concept to be submitted to ESA will doubtless draw heavily on these studies. Due to secrecy agreements with these companies we are not permitted, at this time, to discuss the current stage of their studies.

Introduction

A full and deep understanding of stellar formation and evolution is central to much of astrophysics. In particular, stars are the basic "clocks" with which we can measure ages of stellar systems within our galaxy, and thus set up and calibrate age estimators in the Universe on larger scales. For instance, dating stellar members of the different components of galactic structure, such as bulge, halo, thin disk, thick disc, would lead to fundamental advances in our understanding of galactic structure formation and evolution.

Stars are also responsible for most of the chemical evolution of the Universe, elements being created and destroyed by nuclear burning in their deep interiors, before they are subsequently

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ejected into the interstellar medium at the end of the stars' lives. A clear and reliable understanding of stellar formation and evolution is therefore essential to our description of chemical evolution of galaxies and of the Universe.

A good knowledge of the evolution of cool solar-type stars is also crucial for our understanding of the past and future evolution of the sun and solar system. Finally, stellar interiors constitute laboratories for studying physical processes such as e.g. convection or nucleosynthesis in extreme conditions that cannot be reproduced on Earth.

The question of the existence of life outside the Earth has been of concern to mankind for several thousand years. Today, one decade after the discovery of the first giant exoplanet, and with the prospect of detecting soon the first telluric exoplanets after the launch of CoRoT (Baglin et al. 2002) in 2006, then of Kepler (Borucki et al. 2003) a couple of years later, we are entering the era when scientific answers to this fundamental question can be envisaged.

Planet formation and evolution theory is at the centre of this problem. In order to understand the origin of life and to determine whether and where life is likely to exist elsewhere in the Universe, a full and reliable understanding of planet formation and evolution is absolutely necessary.

Understanding the processes of star and planet formation and the subsequent evolution of stellar interiors, stellar surfaces and of planetary systems is thus a prerequisite for future progress in most areas of astrophysics and in the scientific and philosophical approaches of the origin of life in the Universe.

Star and planetary system evolution

Theory of stellar evolution has undergone major progress in the last decades. In particular, improvements in the description of opacities, equation of state and thermonuclear reaction rates have resulted in a better agreement between models and observations.

In spite of this progress in our understanding of microscopic physics in stellar interiors, our description of some physical processes controlling stellar structure and evolution is subject to major uncertainties. Convection and various other mixing and transport processes are poorly understood and yet play a major role in stellar evolution. Some of these processes, such as mixing and diffusion in stellar cores for main sequence stars, are crucial in determining their evolution timescales, and therefore need to be understood and taken into account for measuring stellar ages. Our current poor knowledge of some (if not all) of these processes is usually compensated in our modelling by some poorly constrained parametrization, and therefore the resulting stellar ages are model dependent and often unreliable.

One of the consequences of this unsatisfactory modelling is that the ages of the oldest globular clusters are still very uncertain, and for some values of the model free parameters can still be higher than the estimated age of the Universe (van den Bergh 1995, Clementini & Gratton 2002, Krauss & Chaboyer 2003). Additionally, the relatively large adopted value of the core overshooting parameter needed to fit young open cluster data (e.g., Mermilliod & Maeder 1986) is in contradiction with recent asteroseismic estimates of 0.1 (expressed in the local pressure scale height) for this parameter for field β Cephei stars (Aerts et al. 2003, Pamyatnykh, Handler & Dziembowski 2004). This clearly points out that our current knowledge of convective and rotational mixing processes inside massive stars is very incomplete, resulting in huge uncertainties in stellar masses and ages of supernova progenitors. In general, uncertainties in convective overshooting lead to uncertainties in the ages of open clusters up to a factor of two (e.g., Perryman et al. 1998). Considering these difficulties and uncertainties, it must be admitted that the age ladder of the Universe, which rests on stellar age estimates, is still highly unreliable.

Our modelling of stellar interiors and stellar evolution therefore needs to be seriously improved. The situation for the Sun has evolved considerably with the advent of helioseismology, which has provided precise insight into the properties of the solar interior (e.g. Christensen-Dalsgaard 2000). The inversion of solar oscillation frequencies has led to the determination of the sound speed in most of the Sun, providing detailed tests of models of solar internal structure. The analysis of frequency splittings has provided measurements of the solar internal rotation to very high accuracy. Based on this very positive experience, it is clear that asteroseismic investigations, i.e. measurements of oscillation frequencies, amplitudes and lifetimes of a large number of stars of various masses and ages constitute the only and necessary tool to develop and operate to constrain efficiently our modelling of stellar interiors, and improve our understanding of stellar evolution (e.g., Roxburgh 2004).

Similarly, we do not yet have a sufficient understanding of planetary system formation and evolution. Detections of giant exoplanets in the past decade have revealed a large variety and complexity of configurations in exoplanetary systems, which was totally unexpected. Major questions and uncertainties remain, which hamper our progress in understanding the formation and evolution of planetary systems.

The distribution of characteristics of exoplanets and of their orbits is unknown. In particular, we have no indication on the distribution of planets with sizes and masses significantly smaller than those of gaseous giant planets. The extension of our knowledge of the frequency and characteristics of exoplanets toward lower masses, down to terrestrial planets, may reveal further surprises. The first planets with masses corresponding to those of icy planets have been discovered in the past year, but their nature (Very large rocky cores? Remnants of evaporated giant planets?) remains at present obscure.

Although some important information will be obtained by CoRoT and later on Kepler, a full statistical description of exoplanetary systems, down to masses and sizes of a fraction of those of the Earth, will be out of reach of these upcoming missions. Yet such a description is a prerequisite for any decisive advance in this field.

In particular, it is only through the tight constraints derived from a full and reliable knowledge of the properties of planets, their orbits and their parent stars that we will progress in our understanding of the mechanisms controlling orbital eccentricities and planet migration (Namouni 2005). The connection between giant planets and the metallicity of their parent stars is still mysterious, and its investigation also requires good statistical knowledge of planet and parent star properties. In particular, asteroseismology has the potential to measure directly the chemical composition difference between the inner part and the external convective zone of a star, that would be present if the high metallicity of planet hosts was due to the ingestion of planetary material (Bazot & Vauclair 2004).

Necessary observational constraints

We clearly lack observational constraints for studying the formation and evolution of stars, of their planetary systems, and of their magnetic fields. These problems being intimately related, their investigations must optimally be conducted jointly. In other words, the constraints that we need to gather on the distribution of planet characteristics, on the internal structure of stars and their evolution, and on the distribution and strength of magnetic fields at the surface of stars, must be obtained by *observing the same sample of stars*.

The best way to obtain the distribution of exoplanet sizes and orbital elements is certainly the observation of planetary transits by long-term monitoring in ultra-high precision visible photometry. The same instrumental technique can also be used to detect and measure stellar oscillation modes in order to probe their internal structure via asteroseismology. This approach is at the centre of the CoRoT mission.

The science objectives outlined above clearly necessitate space-based observations. First, the ultra-high photometric precision needed to detect planetary transits from small- and medium-size telluric planets, as well as to detect and measure low amplitude stellar oscillations, cannot be achieved from the ground because of scintillation noise. Second the very high duty cycle needed to avoid side lobes in the oscillation power spectra and to optimize the transit detection probability, also calls for space-based observations.

Proposed observational concept

The basic observational concept proposed here consists in following these three complementary approaches on the same stars. The strategy is to identify a sample of more than 100 000 stars, and to perform on all of them a long-term high precision monitoring in visible light, with the following objectives:

- search for planetary transits in broadband visible intensity measurements; characterize the detected transits (depth, duration, period, shape,...) and derive the characteristics of the transiting planets and their orbits;

- detect oscillation modes in broadband visible intensity measurements; measure their frequencies, amplitudes and lifetimes, and derive constraints on internal structure and internal rotation, e.g. via inversion techniques.

These objectives can be met using the same set of visible photometric observations. Because we need to detect stellar oscillations at least down to solar-like oscillation amplitudes (typically a few ppm), the visible light photometric observations must be performed on stars that are bright enough that such oscillations can be comfortably detected against photon noise. For reasonable values of the instrument pupil size, the limiting magnitude for such observations is around $m_V = 11$.

The search for planetary transits around such bright stars requires a very wide field in order to counterbalance the relatively small density of such stars in the sky. For a wide choice of pointing directions, one can find typically 140 stars brighter than m_V=11 per square degree. The specification for the planetary transit objective would therefore be to monitor a field of at least $30^\circ \times 30^\circ$, in order to include about 100 000 such stars. Such a large number of relatively bright stars would provide us with an unbiased stellar sample in terms of mass, age, metallicity, rotation. It would also include members of open clusters of various ages, as well as old Population II stars.

The duration of the monitoring to be performed on these stars must be of at least 5 years. With such a long duration monitoring, we will be able to detect and characterize planets with orbital periods up to several years. We will also reach a very high precision in the frequency measurements for asteroseismology, and get the opportunity to study changes in mode amplitudes and frequencies along stellar activity cycles.

The detection of earth and sub-earth sized planet transits, as well as the detection and analysis of solar-like oscillations imply stringent requirements in terms of visible photometric precision: photometric noise levels as low as 2×10^{-5} in 1 hr for stars with $m_V = 11$ are necessary for the foreseen exoplanet studies, while a resulting photometric noise level in Fourier space of 10^{-6} in 2 weeks for stars with $m_V = 11$ is a prerequisite for asteroseismology of solar-like stars in the same sample. These demanding requirements impose a large collecting area, of the order of $1\,\mathrm{m}^2$.

An example of instrumental concept

In this section, we present an instrumental concept that would meet the requirements listed above. We stress that this is nothing other than an illustrative example, and that alternative options are possible, and are currently being considered in industrial studies by Astrium and Alcatel/Alenia and will doubtless influence the final version of the mission concept to be submitted to ESA. At the present time these studies are subject to a secrecy agreement and so unfortunately their results cannot be presented here.

The major difficulty comes from the need to cover a very wide field (30°), with a large collecting area ($1m^2$). One solution is to use a large number of small pupil, short focal length optics. The short focal length made possible by the use of small pupils yields a wide optical field, while the large number of unit elements ensures a large effective collecting area.

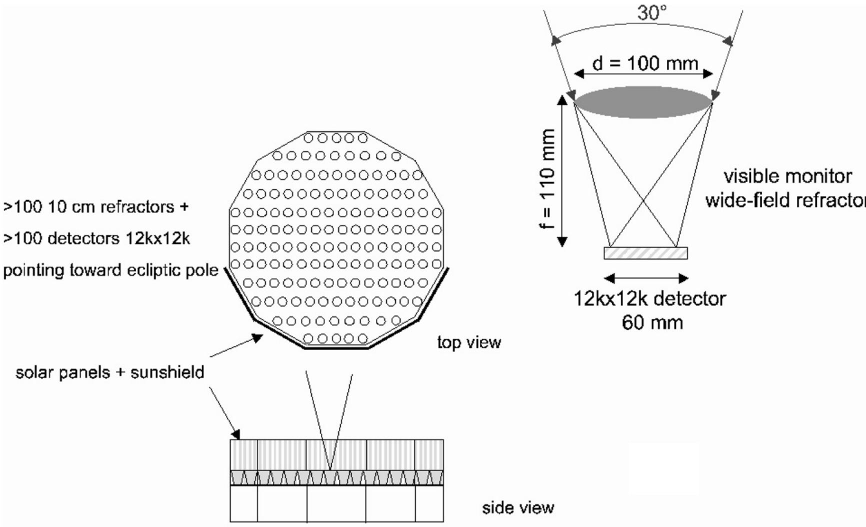

Figure 1: An example of instrumental configuration. The instrument includes 100 refractors with pupils of 100 mm all looking at the same 30° × 30° field. Each visible refractor has its own focal detector, made of one single 12k × 12k visible detector, with 5 μm pixels, or a mosaic of smaller detectors, covering up the available 6 cm focal plane.

This illustrative example of instrumental concept (Fig. 1) calls for some technological developments and changes in design. For example it is probably necessary to use reflecting telescopes to reduce the mass, the development of large format, small pixel CCDs is certainly a challenging issue to be studied in detail in the coming months and years. Other points to be studied in relation to this concept include miniaturized electronics and powerful on-board computing facilities. Note however that most of these developments will build on heritage from previous missions and/or previous studies, such as Gaia or Eddington, so that the concept presented here can certainly be developed at low technological risk.

Advantages of the proposed concept

Exoplanet science

Our proposed observational concept concentrates on the observation of a large number of bright and nearby stars to search for planetary transits. The relatively short distance to the targets is compensated by the very large field size, to finally allow us to probe a large volume of the galaxy. This is in contrast to previous approaches, such as CoRoT, Kepler or Eddington, which are designed to survey a large volume of the galaxy by observing faint and distant stars in a much smaller field.

Because the present concept focuses on bright and nearby stars, still providing a fully unbiased sample, the use of a large collecting area on relatively bright targets will yield high signal-to-noise ratios in the light curves, thus allowing us to detect small planets, and to characterize the transit shapes with a higher precision. In addition, the brightness of the surveyed stars makes possible their subsequent observation in high resolution spectroscopy. The proximity of some of these objects also provides us with the opportunity of performing detailed astrometric follow-up observations, as well as interferometric imaging of the detected planets.

Stellar interiors

The seismological observations of the proposed concept will give us the possibility to study stellar oscillations down to solar-like level for more than 100 000 stars, of all masses and ages. This is a considerable step forward compared to currently planned missions: it represents more than 1000 times the stellar sample monitored by CoRoT, and more than five times the sample that was planned for the Eddington mission. This impressive star sample represents a significant fraction of the targets that will be observed by Gaia/RVS, and for which we will provide an estimate of their age. The age observable, missing from the Gaia/RVS science, will complete nicely the space and velocity-space coordinates provided by Gaia, and bring us a full characterization of the surveyed galactic populations. Finally, the proposed five-year duration will yield very high precision on oscillation frequencies, and thus a very good precision on internal structure and rotation.

Summary and conclusion

The observational concept proposed in this paper will allow us to study at the same time and on the same targets two fundamental problems of today's astrophysics: the characterization of exoplanets and stellar evolution.

In order to meet these fascinating and challenging objectives, we need to survey a very wide field and monitor more than 100 000 stars at a time, to reach a very high precision photometry in the visible, and to perform very long duration monitoring. This concept has its place within an overall European roadmap for the study of star and planet evolution. As of the end of 2006, the pioneering mission CoRoT will open the way by looking for the first telluric exoplanets and by performing the first high precision seismology studies of a few bright stars. The mission concept we have described here goes *far beyond* that of the Eddington mission (sadly cancelled by ESA due to budgetary constraints) and as a consequence, is more challenging from a technical point of view, thus requiring a new mission concept assessment study. The very large number of targets will allow us to study the broad context of the life of stars and planets from one mission for hundreds of thousands of stars in our Galaxy at once.

Gaia will provide the most complete investigation of stellar fundamental parameters for millions of stars. The concept we propose here will complete this view by (i) providing a measurement of the age of a significant fraction of the Gaia targets, (ii) investigating the internal structure and rotation of stars of all masses and ages, (iii) characterizing with high accuracy exoplanetary systems together with their central stars.

The statistical knowledge acquired on exoplanetary systems by missions like CoRoT, and the mission concept proposed here, can be used to optimize the strategy of future interferometric imaging missions such as Darwin and subsequent more ambitious interferometric missions such as that submitted to ESA by Catala and Roxburgh (2005) in response to their call for ideas for the future science programme of ESA.

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