THE LIFE OF STARS AND THEIR PLANETS

C. Catala[1], C. Aerts[2], S. Aigrain[3], E. Antonello[4], T. Appourchaux[5], M. Auvergne[1], A. Baglin[1], P. Barge[6], M. A. Barstow[25], F. Baudin[5], P. Boumier[5], A.C. Cameron[7], J. Christensen-Dalsgaard[8], G. Cutispoto[9], H. Deeg[10], M. Deleuil[6], S. Desidera[27], J.-F. Donati[12], F. Favata[13], B.H. Foing[13], J. Gameiro[14], R. Garcia[15], R. Garrido[16], K. Horne[7], A.F. Lanza[9], A.C. Lanzafame[26], A. Lecavelier des Etangs[17], A. Léger[5], M. Mas-Hesse[18], S. Messina[9], G. Micela[19], E. Michel[1], M. Monteiro[14], B. Mosser[1], A. Noels[20], I. Pagano[9], G. Piotto[11], E. Poretti[4], H. Rauer[21], T. Roca-Cortes[10], M. Rodono[28], D. Rouan[1], I. Roxburgh[1,22], J. Schneider[1], K. Strassmeier[23], S. Turck-Chièze[15], S. Vauclair[12], A. Vidal-Madjar[17], W.W. Weiss[24], and P. Wheatley[25]

[1]Observatoire de Paris, 5 place Jules Janssen, 92195 Meudon Cedex, France
[2]Katholieke Universiteit Leuven, Belgium
[3]Institute of Astrophysics, Cambridge, UK
[4]INAF - Osservatorio Astronomico di Brera, Merate, Italy
[5]Institut d'Astrophysique Spatiale, Orsay, France
[6]Observatoire Astronomique Marseille-Provence, France
[7]University of St-Andrews, Scotland, UK
[8]Aarhus Universitet, Denmark
[9]INAF - Osservatorio Astrofisico di Catania, Italy
[10]Instituto de Astrofisica de Canarias, Spain
[11]Universita' di Padova, Italy
[12]Observatoire Midi-Pyrénées, Toulouse, France
[13]Astrophysics Division - Research and Science Support Department of ESA, ESTEC, The Netherlands
[14]Universidade do Porto, Portugal
[15]Service d'Astrophysique /DAPNIA, CEA, Saclay, France
[16]Instituto de Astrofisica de Andalucia, Granada, Spain
[17]Institut d'Astrophysique de Paris, France
[18]Centro de Astrobiologia (CSIC-INTA), Madrid, Spain
[19]INAF - Osservatorio Astronomico di Palermo, Italy
[20]Université de Liège, Belgium
[21]Deutsches Zentrum für Luft- und Raumfahrt (DLR), Berlin, Germany
[22]Queen Mary, University of London, UK
[23]Astrophysikalisches Institut Potsdam, Germany
[24]Universität Wien, Austria
[25]University of Leicester, UK
[26]Dipartimento di Fisica e Astronomia, Universita' di Catania, Italy
[27]INAF - Osservatorio Astronomico di Padova, Italy
[28]Universita' di Catania, and INAF Headquarters, Rome, Italy

Abstract

We lack a reliable scenario for the formation and evolution of stars and their planetary systems, involving key factors such as magnetic fields and turbulence. We present the case for a mission concept that will clarify these problems and give us a global view of the evolution of combined star and planetary systems. This will be achieved by simultaneously addressing the search for planetary transits in front of a large number of stars, including many nearby stars, the study of their internal structure and evolution via asteroseismology, and that of their magnetic activity, via UV monitoring.

Key words: Stars: structure – Stars: evolution – Stars: magnetic activity – Planets: exoplanets

1. 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 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 it 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.

In this paper, we outline a space mission concept that will address these issues by performing long-term ultra-high precision photometric monitoring in the visible and the UV on a large sample of stars, in order to search for planetary transits, to probe stellar internal structure and investigate stellar magnetic activity.

2. 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 parameterisation, 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; Pamyathnykh et al. 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 2 (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 et al. 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 giants 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?) remain 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.

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 stars properties (Santos 2005). 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).

3. Stellar magnetic fields

It is clear that magnetic fields play a major role at many stages of the evolution of stars and of their planetary systems. Perhaps the most important impact of magnetism in this evolution is related to the loss of angular momentum, without which star and planet formation could not take place. Magnetic fields control the amount of angular momentum loss through stellar winds, by forcing the material escaping the star to carry away the angular momentum acquired at the Alfven radius, which can be several times larger than the stellar radius.

There is a strong cross-influence between the stellar interior and the outer atmosphere dominated by magnetic phenomena whose underlying origin is deeply rooted in the inner regions of the star. Dynamo processes at work in stellar interiors control the intensity and topology of the magnetic field; the resulting magnetic field impacts the angular momentum evolution and thereby the angular velocity gradient inside the star, which is an essential ingredient for the dynamo. Stellar magnetic activity therefore influences the dynamo efficiency, producing a feedback process with a tight interplay between the properties of the stellar interiors and those of the outer atmospheres.

Modelling of the early and later phases of stellar and planetary system evolution cannot ignore these major processes.

The formation of stars and their planetary systems is also affected by magnetic fields. In particular, recent X-ray observations of Orion (Favata et al. 2005) have shown the existence of very long flares loops, connecting the stars with their circumstellar discs. These magnetic fields may affect the disc properties, changing abundances of chemical species and viscosity, thus impacting the formation and subsequent evolution of planetary systems.

Magnetic fields participate in the interaction between a star and its planets, for instance by accelerating particles to high energies in the stellar wind, these particles eventually interacting with the planets. For planets with magnetospheres, the magnetic field also is essential for shielding the planet from hard radiation coming from the star. It has also been suggested recently that giant planets on short period orbits can trigger and/or enhance magnetic activity in sub-planetary regions of the stellar surface (Shkolnick et al. 2005).

Stellar magnetic activity and its interaction with orbiting planets can have a major impact on the genesis of life and its subsequent evolution. Usually considered as a threat for life, one can conjecture that stellar activity can also be a catalyst for life in some particular cases (e.g. Jorissen et al. 2002).

Although magnetic fields are central to stellar and planetary formation and evolution, they have been largely ignored so far in our modelling, or at best grossly parameterized. This situation needs to be improved, and thorough statistical investigations of stellar magnetic fields, and how they relate to stellar and planetary system evolution must be undertaken.

4. 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 center of the COROT and Eddington missions.

Stellar magnetic fields can be studied in large samples of stars by monitoring UV-light variability. Magnetic activity indeed manifests itself as variable emission from the outer atmosphere in both continuum and emission lines in the UV, EUV and soft X-ray domains. Time scales for this variability range from minutes (flares) to hours and days (rotational modulation), up to years and decades (activity cycle). The analysis of the behaviour of UV-light variations, either in broad bands or in carefully selected emission lines, can be used to characterize and map stellar magnetic fields.

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 access to the UV, necessary for monitoring stellar magnetic activity, can only be obtained from space. Finally, the very high duty cycle needed to avoid side lobes in the oscillation power spectra, to optimize the transit detection probability, and to cover the stars' rotational cycles for the analysis of their magnetic activity, also calls for space-based observations.

5. 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 both visible and UV 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;
– detect variations in the UV light curves, either in broadbands or in a set of UV emission lines sensitive to stellar activity; characterize the flaring activity from short-term UV variability; characterize and map surface magnetic fields by analyzing rotational modulation of UV light; study activity cycles by analyzing the long-term variability in the UV.

The first two 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 $30° \times 30°$, in order to include about 120,000 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. Finally, such a long duration will also be crucial in the UV-monitoring segment of the proposed concept to detect and characterize 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 m^2.

Finally, the long-term UV monitoring of the same targets, with the goal of characterizing their magnetic activity, requires a collecting area in the UV of the same order of magnitude, as well as an instrumental configuration providing one or several wide- or narrow-bands sensitive to stellar activity.

6. An example of instrumental concept

In this section, we present one possible 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 currently considered.

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.

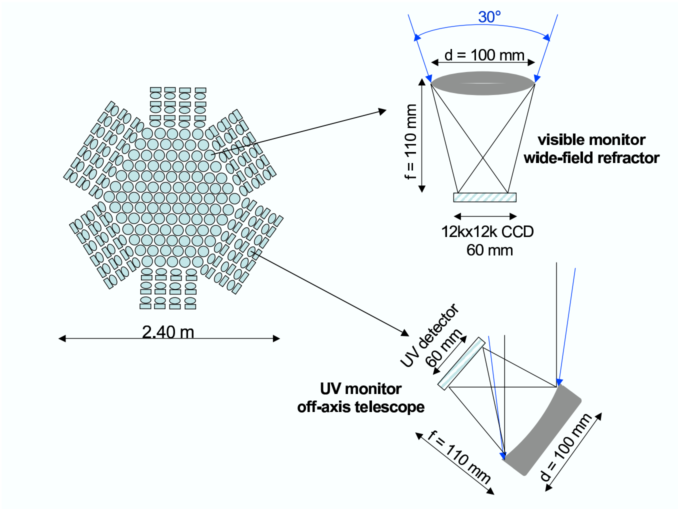

Figure 1. An example of instrumental configuration. The instrument includes 100 refractors with pupils of 100 mm, and 100 off-axis UV telescopes with pupils of 100 mm, all looking at the same $30° \times 30°$ *field. Each visible refractor has its own focal detector, made of one single 12k* $\times$ *12k visible detector, with 5* μ*m pixels, or a mosaic of smaller detectors, covering up the available 6 cm focal plane. The UV detectors attached to the UV off-axis telescopes also have a 6 cm format.*

This illustrative example of instrumental concept (Fig. 1) calls for some technological developments. Among these, 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 onboard 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.

7. Advantages of the proposed concept

7.1. 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, several stringent and well-recognized problems of planetary transit search techniques are much easier to cope with. First of all, the use of a large collecting area on relatively bright targets will yield high signal-to-noise ratios in the lightcurves, thus allowing us to detect small planets, and to characterize the transit shapes with a higher precision. Second, because the surveyed stars are bright, we can achieve a better rejection of false events, such as e.g. the presence of a background eclipsing binary: an eclipsing binary mimicking a planetary transit in front of a star with m_V=11 will need to be 100 times brighter than that mimicking a transit with the same depth for a 16th magnitude star, and therefore will be much more rarely present.

In addition, the brightness of the surveyed stars makes possible their simultaneous analysis in seismology and UV monitoring. It will also be easy to perform accompanying high resolution spectroscopic observations. The short distance 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.

Finally, it is important to note that the expected performances of this concept will be such that terrestrial planets in the habitable zone will be detectable down to approximately m_V=14, extending dramatically the sample of detected planetary systems (Piotto et al., these proceedings).

7.2. 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 120,000 stars, of all masses and ages. This is a considerable step forward compared to currently planned missions: it represents more than 1,200 times the stellar sample monitored by COROT, and more than 5 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 5 year duration will yield very high precision on oscillation frequencies, and thus a very good precision on internal structure and rotation.

7.3. Stellar activity

The UV monitoring of more than 120,000 stars of all types will constitute the first ever gigantic survey for stellar activity, representing e.g. a stellar sample one hundred times larger than that of the Mount Wilson H&K survey for stellar activity (Baliunas et al. 1998). This UV monitoring would extend dramatically our investigation capabilities in the area of stellar activity, which is presently relying on X-ray monitoring, e.g. with the XMM satellite, or as planned with the LOBSTER experiment onboard the ISS.

The possibility to measure stellar rotation rates through rotational modulation of visible and UV flux on a very extended sample of stars will allow us to study the angular momentum evolution of stars older than 1 Gyr, which is presently poorly known.

The measurement of stellar surface differential rotation through a detailed analysis of their visible and UV light curves will provide us with information on one of the basic ingredients of stellar dynamo.

The 5-year duration of the monitoring will allow us to study activity cycles.

Finally, the monitoring of UV light curves will be used to assess the level of noise induced by stellar activity on optical light curves, and give the opportunity to correct for it in planetary transit and seismology studies.

We point out that the concept of UV capabilities as presented here is optimized for monitoring stellar activity. Ideally, one would also want to achieve a setup that allows to monitor the stellar pulsations in the UV domain, because this improves considerably the mode identification (Garrido 2000). It remains to be investigated during an assessment study whether the inclusion of such a UV capability is feasible.

8. Summary and conclusion

The observational concept proposed in this paper will allow us to study at the same time and on the same targets three fundamental problems of today's astrophysics: the characterization of exoplanets, stellar evolution, and stellar magnetic activity and its role in the evolution of stars and planets.

In order to meet these fascinating and challenging objectives, we need to survey a very wide field and monitor more than 120,000 stars at a time, to reach a very high precision photometry in both the visible and the UV, 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 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 road may then continue with the Eddington mission, which, if flown according to the concept of its successfully completed Phase A study, will obtain asteroseismic observations of thousands of stars, including open cluster members, and extend the statistical knowledge of exoplanet characteristics, including telluric planets in the habitable zone. The mission concept we have described here goes *far beyond* the one of the Eddington mission and, as a consequence, is more challenging from a technical point of view, thus requiring a new mission concept assessment study. It will enlarge the number of targets with an order of magnitude compared to Eddington, and its UV capacities 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, as well as magnetic activity 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, Eddington, 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.

References

Aerts, C., Thoul, A., Daszynska, J., Scuflaire, R., Waelkens, C., Dupret, M-A., Niemczura, E., Noels, A., 2003, Science 300, 1926

Baglin, A., Auvergne, M., Barge, P., Buey, J.-T., Catala, C., Michel, E., Weiss, W.W., and the COROT team, 2002, Stellar Structure and Habitable Planet Finding, 1st Eddington Workshop, ESA-SP 485, p. 17

Baliunas, S.L., Donahue, R.A., Soon, W., Henry, G.W., 1998, ASP Conf. Series 154, 153

Bazot, M., Vauclair, S., 2004, A&A 427, 965.

Borucki, W.J., Koch, D.G., Basri, G.B., Caldwell, D.A., Caldwell, J.F., Cochran, W.D., Devore, E., Dunham, E.W., Geary, J.C., Gilliland, R.L., Gould, A., Jenkins, J.M., Kondo, Y., Latham, D.W., Lissauer, J.J., 2003, ASP Conf. Series 294, 427

Christensen-Dalsgaard, J., Däppen, W., Dziembowski, W. A., Guzik, J. A., 2000, in Variable Stars as Essential Astrophysical Tools, C. Ibanoglu (ed.), Kluwer Academic Publishers, p. 59

Clementini, G., Gratton, R., 2002, The oldest stars and the age of the Universe, European Review, Vol. 10, Issue 02, p.237-248

Favata, F., Flaccomio, E., Reale, F., Micela, G., Sciortino, S., Shang, H., Stassun, K., Feigelson, E.D., 2005, ApJS, in press

Garrido, R., 2000, In: Delta Scuti and Related Stars, ASP Conference Series, Vol. 210, p.67, Eds. M. Breger and M. Montgomery

Jorissen, A., Corince C., 2002, Orig. Life Evol. Biosph. 32(2),129

Krauss, L.M., Chaboyer, B., 2003, Science 299, 65

Mermilliod, J.C., Maeder, A., 1986, A&A 158, 45

Namouni F., 2005, Astron. J. 130, 280

Pamyathnykh, A.A., Handler, G., Dziembowski, W.A., 2004, MNRAS 350, 1022

Perryman, M.A.C., Brown, A.G.A., Lebreton, Y. et al., 1998, A&A 331,81

Roxburgh, I.W., 2004, Stellar Structure and Habitable Planet Finding, 2nd Eddington Workshop, ESA-SP 538, p.23

Santos, N.C., 2005, Proc. 13th Cool Stars Workshop, F. Favata et al. (eds), in press

Shkolnik, E., Walker, G.A.H., Bohlender, D.A., Gu, P.-G., Kürster, M., 2005, ApJ 622, 1075

van den Bergh, S., 1995, Science, 270, 1942