Pulsations and planets: the asteroseismology-extrasolar-planet connection

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The disciplines of asteroseismology and extrasolar planet science overlap methodically in the branch of high-precision photometric time series observations. Light curves are, amongst others, useful to measure intrinsic stellar variability due to oscillations, as well as to discover and characterize those extrasolar planets that transit in front of their host stars, periodically causing shallow dips in the observed brightness. Both fields ultimately derive fundamental parameters of stellar and planetary objects, allowing to study for example the physics of various classes of pulsating stars, or the variety of planetary systems, in the overall context of stellar and planetary system formation and evolution. Both methods typically also require extensive spectroscopic follow-up to fully explore the dynamic characteristics of the processes under investigation. In particularly interesting cases, a combination of observed pulsations and signatures of a planet allows to characterize a system’s components to a very high degree of completeness by combining complementary information. The planning of the relevant space missions has consequently converged with respect to science cases, where at the outset there was primarily a coincidence in instrumentation and techniques. Whether space- or ground-based, a specific type of stellar pulsations can themselves be used in an innovative way to search for extrasolar planets. Results from this additional method at the interface of stellar pulsation studies and exoplanet hunts in a beyond-mainstream area are presented.

1 Introduction

The (transiting) extrasolar planet fields and the asteroseismology field see a convergence of instrumentation that culminates in the insight that beyond this purely technical level, a much more fundamental connection exists in the shared desire for the most exhaustive characterization of stellar and planetary systems at all possible with the available diagnostics. I will first sum up the relevant current context with an emphasis on planets around evolved stars, and then specifically address the topic of oscillation timing as a means to detect planets.

In terms of successes to detect planets around evolved stars, the subdwarf B stars as host stars stand out as a group. This class of evolved objects will be introduced, and the difficulties in explaining their sheer existence mentioned. Incidentally, the asteroseismology of subdwarf B stars is also a very active field. The EXOTIME planet searching program will be presented, which takes advantage of the long-term behaviour of these pulsations. Current ideas on subdwarf B evolution, and the potentially crucial role of planets, will be discussed, frequently resorting to the V391 Pegasi system.

2 Extrasolar planet detection methods

2.1 Overview

The first extrasolar planet candidate was observed in 1989, without however being claimed as such at the time. \cite{Latham1989} instead suggested that the sub-stellar companion they had found around HD 114762 probably was a brown dwarf: a class of intensely searched-for objects, yet mostly elusive, at that period, and found to be intrinsically rare in the role of companions to normal stars today.

The first detection of an extrasolar planet around a solar-type star properly published as a “Jupiter-mass companion” was by \cite{Mayor1995}. This companion to 51 Pegasi was immediately confirmed by \cite{Marcy1995}. 51 Pegasi b constitutes the prototype of the hot Jupiters, but it can also be more generally regarded as the prototype for all extrasolar planets discovered with the radial velocity method. While the radial velocity method still is to be credited with the top score in terms of number of planets (and multiple planetary systems) discovered, other discovery methods gain their importance from the fact that the observational biases involved can be significantly different.

Direct imaging, for instance, is obviously biased towards large semi-major axes (e.g. \cite{Kalas2008} \cite{Marois2008}, and probably \cite{Lagrange2009}), whereas radial velocity and transit measurements are biased towards the

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detection of planets on orbits with small semi-major axes (and large masses resp. radii). This correspondence between the radial velocity and transit methods is in a sense a good thing, since transit detections always need to be confirmed by radial velocity measurements in order to secure a planet discovery, while planet candidates from radial velocities detections usually remain candidates as long as the inclination cannot be constrained. For ground-based surveys, the micro-lensing technique is most sensitive in the vicinity of the Einstein radius at 2 - 3 AU (Bennett et al. 2009; actual detections exist for semi-major axes in the range of 0.6 - 5.1 AU).

The timing method, or more precisely, the various timing methods, also constitute indirect methods. While exploiting the same stellar "wobbling" effect induced by an unseen companion that is put to use in the radial velocity method, it measures the varying light travel time from the star(s) to the observer in the course of a "wobbling" cycle. Its amplitude (a direct measure of the projected semi-major axis of the orbit followed by the central object) increases with large companion masses, but also with large separations. Despite this increasing sensitivity towards wider orbits, the fact that the observational time base required for a detection increases for longer orbital periods also must be factored into the overall detection probability. Exactly as in the case of detections from radial velocity variations, candidates discovered with any of the timing methods suffer from a systematic uncertainty in the mass determination whenever the orbital inclination remains unknown.

A more detailed overview of the available planet detection methods with an emphasis on their respective sensitivity to masses has been given by Perryman (2000); an updated version with planet detection counts up to early 2010 is given in Fig. 1.

2.2 Planetary systems around evolved stars

The majority of extrasolar planets known today were found around solar-like stars. On the one hand, this has practical reasons - both the number of lines in the optical and their sharpness decreases towards earlier spectral types, while later spectral types tend to show augmented spectral variability due to activity, making small periodic radial velocity signals harder to detect. On the other hand, any dedicated searches for solar system analogues and Earth-like planets will obviously primarily target solar-like stars. In the quest to understand how our own solar system including the Earth has formed, it seems plausible to assume that both the knowledge of the frequency of similar systems as well as an overview of just how differently planet formation has proceeded elsewhere are important ingredients.
For stars evolving off the main sequence, the radial velocity method remains applicable in the red giant regime. It has turned up a total of 27 detections around G and K giants that add to the diversity of systems known. Among the initial discoveries were those by Frink et al. (2002), Hatzes et al. (2003), Hatzes et al. (2006), and Döllinger et al. (2007). For all stars evolved beyond the first red giant branch, however, the method that has most successfully been applied to detect extrasolar planets so far is the timing method.

### 2.3 Timing methods

The timing method actually comes in a variety of flavours. In all cases, a mechanism intrinsic to the central object provides a stable clock the time signal of which reaches the observer with a delay or in advance to the mean arrival times when a further body causes a cyclic displacement (wobble) of the "clock". As a side note, the associated change in period of the clock due to the Doppler effect is typically much smaller than the light travel time delays.

The most prominent example for a central object’s clock are the pulses from rapidly rotating neutron stars. Pulsar planets were discovered in this way to orbit PSR 1257+12 by Wolszczan & Frail (1992), and confirmed by Wolszczan (1994). A further detection was reported for PSR B1620-26 by Backer (1993), Thorsett et al. (1993), and Backer et al. (1993). This system in the globular cluster M4 is known for its assortment of components, with a white dwarf in a tight orbit around the pulsar (Thorstset et al. 1999), imaged using HST by Richer et al. (2003), so the planet may be referred to as a circumbinary planet.

In a further approach, the timing method specifically targets circumbinary planets by design. The clock in this case are frequent, sharp eclipses in a close central binary system. Eclipse timing has uncovered sub-stellar companions to subdwarf B stars (sdB, see section 4) in HW Vir-like binary systems. Eclipse timing has uncovered sub-stellar companions are frequent, sharp eclipses in a close central binary system. Tertiary detections have been reported for the polar DP Leo (Qian et al., 2010a), for the planetary planet in the binary γ Cephei AB, where the planet orbits the primary K subgiant component (early speculations from radial velocity measurements by Campbell et al. 1998) were first confirmed by Hatzes et al. 2003, and refined through a direct detection of the secondary M dwarf component by Neuhäuser et al. 2007.

A variant of this method is to look for timing residuals in known planetary transits in order to uncover additional planets in the system.

The third possibility is to resort to stellar oscillations as a clock. This lead to the first discovery of a planet around a subdwarf B star, V391 Pegasi, by Silvotti et al. (2007). The existence of this system suggested the possibility that a planet in an orbit similar to that of the Earth may have survived the red giant expansion of its presumably single host star, and has triggered follow-up searches for comparable systems. I will come back to this application in section 3.3.

### 3 Stellar oscillation - extrasolar planet links

An obvious benefit of high-precision photometric time series of planet-hosting stars (such as those obtained in ambitious transit searches) is that the host star can additionally be characterized in detail with asteroseismic methods if it oscillates.

#### 3.1 Asteroseismology

For small perturbations to a spherical equilibrium solution, an infinite series of non-radial modes, with the radial modes included as a special case, can occur (which can be described by nodal planes in two angular directions, and spherical nodal surfaces in the radial direction), leading to multi-periodic frequency spectra. The equilibrium is restored by the actions of pressure and buoyancy, with one of the two usually dominating in a particular region of the star. The number of actually measurable frequencies depends on whether the corresponding modes are excited (i.e., if a driving mechanism is converting radiative energy or, temporarily, convective movement into pulsational kinetic energy), and on whether they are observable as photometric or radial velocity variations (i.e., if the mode geometry yields a detectable net effect in the integrated observables).

Given appropriate modelling capabilities, the density structure of a star can be inferred from observations of a sufficiently large number of excited eigenmodes that probe the interior conditions differentially. While the exact analysis approach can vary depending on the class of variables considered, important fundamental parameters that can be derived from this exercise are the stellar mass, radius and (depth-dependent) chemical composition.

In solar-like pulsators, oscillatory eigenmodes are excited stochastically by convection. The known pulsations are p modes (acoustic modes, with displaced material restored by the action of pressure), although g modes (gravity modes, action of buoyancy) are also thought to exist in the deep interior of the sun. Considering that derivatives of the local equilibrium gravity and radius can be neglected in this case, approximations for high radial order can be found. For acoustic modes described within the asymptotic theory, one finds a regular frequency spacing for modes of the same

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1 As a side note, a different example for a hierarchical system is the planet in the binary γ Cephei AB, where the planet orbits the primary K subgiant component (early speculations from radial velocity measurements by Campbell et al. 1998) were first confirmed by Hatzes et al. 2003, and refined through a direct detection of the secondary M dwarf component by Neuhäuser et al. 2007.

2 Provisional reports on more detections are also out on the W UMa-type eclipsing binaries NY Lyr and DD Mon (Qian et al. 2009a).
low angular degree corresponding to subsequent radial orders. The large frequency separations, along with modifications introduced by considering the effect of different degrees leading to additional small frequency separations, together allow the definition of valuable diagnostic tools. This includes the famous échelle diagrams, as well as the ’asteroseismic HR diagram’ which allows to relate the two observables large and small frequency separation directly to the masses and ages of solar-like stars.

3.2 Connection with solar-like oscillations

The precise stellar parameters available through asteroseismic investigations contribute to answering a number of key questions in extrasolar planet research. One of the early noteworthy examples was the idea to investigate the scenarios for the origin of the enhanced metal content of µ Arae (HD 160691), host to a system of at least four planets, with asteroseismic methods. From ground-based radial velocity observations [Bouchy et al. 2005], [Bazot et al. 2005] attempted to decide whether the overmetallicity was limited to the outer layers (accretion scenario) or was present throughout the star (resulting from enhanced metallicity in the original proto-stellar cloud). The latter scenario with enhanced planet formation rates in intrinsically metal-richer star-forming clouds has now been generally accepted, a result incorporated into the more recent analysis by [Soriano & Vauclair 2009] that has in addition uncovered a high helium abundance. It will remain to be seen if contributions from asteroseismology will also be able to help solve the possibly related mystery of enhanced lithium depletion in planet-hosting stars [Israelian et al. 2009].

Fundamental links between the two programmes of the space mission Corot, the exoplanet search and the asteroseismology programme, have been pointed out by [Vauclair et al. 2006] (see also [Soriano et al. 2007; Vauclair 2008]). In Corot these two programs are conducted with separate pairs of detectors operated with different instrumental setups: an on-focus setup with dispersion through a bi-prism sampled every 512 s in the exoplanet field, and a highly out-of-focus setup sampled every 1 s in the seismology field.

While a smaller technical dichotomy continues to exist with the long (30 min) and short (1 min) cadence readout modes for the individual apertures on the Kepler satellite’s detectors, the boundaries start to dissolve here since the sampling is at best loosely associated with the classification of a target as belonging to the planet-hunting core program or a program such as the asteroseismic investigation, and can simply be re-assigned. Kepler has demonstrated its capabilities early on in the mission schedule with observations of the known transiting exoplanet host HAT-P-7 [Borucki et al. 2009]. HAT-P-7 has in the meantime been further characterized through an analysis of its simultaneously discovered solar-like oscillations [Christensen-Dalsgaard et al. 2010].

Kepler has now also delivered its first five genuine extrasolar planet discoveries [Borucki et al. 2010]. The routine analysis of solar-like oscillations in newly-discovered planet-hosting stars, as well as the analysis of a large variety of asteroseismology targets of interest to the pulsation science community, have been institutionalized in the Kepler Asteroseismic Investigation (KAI) and the Kepler Asteroseismic Science Consortium (KASC, see Christensen-Dalsgaard et al. 2008), and in particular the first results in Gilliland et al. 2010 and Christensen-Dalsgaard et al. 2010. The importance of determining the stellar radius as accurately as possible stems from the circumstance that a transit light curve yields the radius ratio between star and planet. In order to derive the transiting planet’s absolute radius the value of the stellar radius must be known. Together with the planet mass determined from the confirmation radial velocity curve (again, the stellar mass must be known), the planet’s mean density is found. In the proposed Plato mission (e.g. Catala & ESA Plato Science Study Team, 2009), the high-precision determination of planet host star radii and other fundamental stellar parameters from asteroseismology is an integral part of the planet hunting and characterization concept.

3.3 Connection with coherent oscillations

The above considerations could in principle with the same rationale be extended to planet-hosting stars that exhibit pulsations other than solar-like. Well beyond this, the striking capabilities in particular of Kepler evidently open many possibilities for genuine asteroseismological applications that target questions in many areas of stellar astrophysics. This includes the classical pulsators which, instead of being stochastically excited as the solar-like stars, exhibit unstable modes driven by the κ mechanism, with topical applications extensively described by [Gilliland et al. 2010].

The standard asteroseismic exercise derives the instantaneous structure of a star, often relying on model structures from full evolutionary models in the process. As an extension, period changes in the oscillatory eigenfrequencies due to evolutionary effects can be considered as an additional constraint to find the best solution in parameter space. Given a series of evolutionary models already subjected to a stability analysis, the rate of change \( \dot{P} \) of modes in a specific model can be determined without too much trouble. Due to the typically very long evolutionary time scales involved, measuring the secular evolution in real stars is observationally expensive and somewhat more complex.

An example of a class of objects where pulsators can be found that prove to be coherent and stable on time scales of many years are the ZZ Ceti variables on the DA white dwarf cooling track. The pulsations in these objects are due to the recombination of hydrogen in a narrow temperature range, leading, via the associated increase of the opacity in the outer layers, to the manifestation of low-degree low-order g modes. In contrast to the millisecond pulses in spin-up pulsars, and also in comparison to the pulse duration in normal “slow” pulsars, the pulsation periods in white dwarfs are
much longer: of the order of a few minutes. The precision that can be reached in determining the clock rate is hence accordingly lower, and long-term changes are more readily analyzed using O–C techniques, instead of determining \( P \) directly as the derivative of a series of quasi-instantaneous \( P \) measurements over time.

Measurements of \( \dot{P} \) and its interpretation in the context of cooling times exist for a small number of suitable pulsating white dwarfs: PG 1159–035 (Costa et al. 1999; Costa & Kepler 2008), G117-B15A (Kepler et al. 1991; Kepler et al. 2000, Kepler et al. 2005), and a larger sample of a total of 15 objects investigated by Mullally et al. (2008). It was quickly recognized (e.g. by Provencal 1997) that the influence of a possible unseen companion can be measured as a side effect from the same data. Applying the ideas of the timing method (section 2.3) has given the long-term photometric monitoring of pulsations in white dwarfs and related objects a new spin as a means to search for planets around evolved stars. With respect to previous work, the efforts by Mullally et al. (2008) show a shift of focus to that effect. Their proposed planet candidate around GD 66 has however remained unconfirmed.

The same measurements are possible for a different group of compact oscillators, the subdwarf B stars (see below), a quantitatively uncommon feeder channel for white dwarfs. The rapid pulsations in subdwarf B stars, of the order of minutes just as in the ZZ Ceti white dwarfs, are generated via a \( \kappa \) mechanism, providing potentially suitable conditions for reasonable long-term coherence. Yet, results have only been published for one pulsating subdwarf B star so far, V391 Pegasi (aka HS 2201+2610). As stated in section 2.3, these measurements, simultaneously to \( \dot{P} \), revealed the presence of a companion with a planetary mass. The possible reasons for this initially unexpected, instant success, sometimes jokingly referred to as ”100% discovery rate”, are worth a more in-depth investigation.

4 Hot subdwarf stars

4.1 Evolution

Subdwarf B stars (sdBs) are subluminous hot stars that are found in an effective temperature range from 20 000 K to 40 000 K at surface gravities between about 5.0 and 6.2 in \( \log (g / \text{cm s}^{-2}) \), and that can in many cases be identified with evolved stellar models on the extreme horizontal branch (EHB). Their masses are expected to peak around the value for the He core flash at 0.46 \( M_\odot \). As is true for all horizontal branch stars, extreme horizontal branch stars have a He burning core but, due to previous significant mass loss, no H-shell burning in their thin hydrogen shells. The thinness of the shell leads to their blue appearance, so that the flux from hot subdwarfs (including the hotter sdOs) contributes significantly to the UV excess observed in galaxy bulges and elliptical galaxies. A great recent review of the observational properties of hot subdwarfs including binarity, kinematics, as well as current modelling capabilities to describe their atmospheres, interiors, and evolutionary history, can be found in Heber (2009). The most puzzling question about hot subdwarfs remains what the precise evolutionary status of these core-helium burning or even more evolved objects really is. Here I only focus on how to possibly produce the sdB type. The basic problem in the standard single-star evolutionary scenario is to shed the hydrogen envelope almost entirely just before or at the moment of the He flash. This would require ad hoc strong mass loss through stellar winds for a certain fraction of stars upon reaching the tip of the first giant branch. Explaining the formation of subdwarf B stars in the context of binary evolution is therefore now generally favoured over single-star scenarios (Han et al. 2003, 2002).

Following the overview by Podsiadlowski et al. (2008), three genuine binary formation scenarios, and additionally the merger scenario, can be distinguished. All three of the binary scenarios involve Roche-Lobe overflow (RLOF), each at different stages and under different conditions.

In the ”stable RLOF + CE” channel, the system initially goes through a first mass-transfer phase with stable RLOF that turns the evolving component into a He white dwarf. When the second component, the future subdwarf B star, then evolves to become a red giant, the second mass-transfer phase can happen dynamically. This unstable RLOF, where the matter transferred cannot all be accreted by the He white dwarf, leads to the formation of a common envelope (CE). After spiral-in and envelope ejection, the resulting system consists of the He white dwarf and the sdB – the core of the giant with its envelope removed – in a short-period binary (< 10 days).

In the ”CE only” channel, unstable RLOF occurs when the future subdwarf B star starts transferring matter to a lower-mass main-sequence companion near the tip of the first giant branch. The ensuing common-envelope phase again leads to a closer final configuration of the resulting system, which will consist of a low-mass main sequence star and the sdB in a short-period binary (< 10 days).

Besides these two common-envelope channels (involving unstable RLOF), the ”stable RLOF” channel can also produce sdBs. Stable Roche-Lobe overflow can occur when the future subdwarf B star starts transferring matter to a main sequence companion at mass ratio below \( \sim 1.2 \). As before, this happens near the tip of the red giant branch, but this time the system more likely widens due to the mass transfer. The resulting system consists of a main sequence or subgiant star and the sdB in a wide binary (\( \gtrsim 10 \) days).

The problem with all of the above binary scenarios is that (apparently?) single sdBs also exist. In addition to the single star scenario involving variable mass loss as mentioned above, a further possibility to produce these are mergers. In the ”merger” scenario, two He white dwarfs in a close system, produced while undergoing one or two common envelope phases, spiral towards each other due to angular momentum loss via gravitational radiation until the
less massive one gets disrupted and its matter accreted onto the more massive component. At a critical mass, the accretor can ignite helium fusion and the merger product would hence indeed turn into a single sdB.

In the confrontation with observations, both the types of companion found in close systems (white dwarf or low-mass main-sequence stars) as well as the close binary frequency are roughly as expected when the above merger channel is considered. Yet observationally, the mass spectrum for the companions is broader than expected from the standard formation scenarios for sdB+WD, sdB+dM and single sdBs. On the low-mass end, it can be argued to comprise the V391 Pegasi planet and, possibly, further secondary sub-stellar companions. Four companions with unusually high masses have also been reported; according to Geier et al. (2009b, 2010, 2008), the massive compact companions found from radial velocity variations must at least be heavy white dwarfs or in two cases even neutron stars or black holes.

While the problem of sdB formation has not been fully solved, the subsequent evolution of a subdwarf B star towards the white dwarf cooling sequence is more straightforward. One interesting characteristic is that this evolution, due to the thinness of the outer layers, bypasses the asymptotic giant branch, as was noted early on by Dorman et al. (1993). Another aspect is that the sdB-dM close systems constitute potential progenitors for cataclysmic variables. Furthermore, given the variety of configurations in which sdBs are found as one component, the diversity of possible progeny systems is not restricted to pre-CVs.

All of the above, while far from understood in the details, implies that the sdB’s stellar core as it looks like after the first giant branch – or after a merger – is almost laid bare. It is hence very well accessible to asteroseismological methods.

### 4.2 Pulsating subdwarf B stars

Only a small fraction of the sdBs show pulsational variations, with non-pulsators also populating the region in the HRD where the pulsators are found. There are p- (pressure-) mode and g- (gravity-) mode types of pulsation.

The rapidly pulsating subdwarf B stars (sdBVr) were discovered observationally by Charpinet et al. (1997). The short periods of these p-mode pulsators are of the order of minutes and have amplitudes of a few tenths mmag. These pulsations were independently predicted to exist by Charpinet et al. (1997), who in this initial and subsequent research papers explain the driving to result from a \( \kappa \) mechanism due to a Z-opacity bump accumulated by radiative levitation.

The longer periods in the slowly pulsating subdwarf B stars (sdBVs) range from 30 to 80 mins at even lower amplitudes of a few mmag. This group of g-mode pulsators was discovered by Green et al. (2003) and has been explained to pulsate due to the same \( \kappa \) mechanism as the sdBVr type by Fontaine et al. (2003).

A number of objects are known that show both types of mode simultaneously and are referred to as hybrid pulsators, or sdBVrVs in the nomenclature of Kilkenny et al. (2010) that is used here. These hybrids lie in the overlapping region between the hotter short-period and the cooler long-period pulsators. The prototype and a prominent example is HS 0702+6043. Its rapid pulsations were discovered by Dreizler et al. (2003), and subsequently the slower ones by Schuh et al. (2006, 2005). Further examples can be found in Schuh (2008) and references therein. It should however be noted here that the planet host star V391 Pegasi (HS 2201+2610) is also among the hybrids. It has five p modes (Østensen et al. 2001b; Silvotti et al. 2002) and at least one g mode (Lutz et al. 2009a, 2008).

Exploiting the sdBVr asteroseismologically has the potential to test diffusion processes and has lead to a first mass distribution for subluminous B stars (Charpinet et al. 2008; Fontaine et al. 2008; Østensen 2009 and references therein.) On the other hand, the extent of the instability region for the sdBVs, but in particular the existence of the sdBVr, has challenged details of the input physics for the models. The actual composition of the ‘Z’ in the Z bump (iron, nickel) as well as the role of opacities have been discussed in this context (Jeffery & Saio 2006, 2007). While, quite similarly to the findings for the sdB variables, using updated Opacity Project (OP) instead of OPAL opacities also improves the situation in \( \beta \) Cep and [SPB] variables, the opposite is the case in the sun with helioseismology. The most appropriate opacities are therefore still under discussion.

Further open questions in this field are the co-existence of pulsators and non-pulsators, and also the origin of the amplitude variability observed in a number of sdBVs (Kilkenny, 2010).

### 4.3 Sub-stellar companions of subdwarf B stars

When a companion with planetary mass was found around the hybrid pulsating subdwarf B star V391 Pegasi with the timing method, this indicated that a previously undiscovered population of sub-stellar companions to apparently single subdwarf B stars might exist (Silvotti et al. 2002a, 2007).

As for low-mass tertiary bodies around HW Vir-like systems detected by eclipse timing, Lee et al. (2009) have reported two planetary companions around the system HW Vir itself. Qian et al. (2009a) put the mass of the tertiary body in the HS 0705+6700 system in the range for brown dwarfs. Still unconfirmed detections by Qian et al. (2010c) exist for HS 2231+2441 and NSVS 14256825.

A different type of detection has been put forward by Geier et al. (2009a, 2010), who report measurements of radial velocity variations in HD 149382 indicative of a planetary companion, variations which if real are indicative of a close sub-stellar companion in a 2.4 d orbit. Based on the above and this finding (that yet has to be confirmed), these authors also argue for a decisive influence of sub-stellar companions on the late stages of stellar evolution.
Fig. 2 Photometric data obtained with the 1.2 m MONET/North telescope during a period of 2 weeks in May 2005, showing the pulsations in the light curve of V391 Pegasi. Starting from a mean intensity of unity on the first night, subsequent observations are shifted downward by a fixed offset each night. The actual data points (black dots) are overlaid with model for the pulsations in red. One such run spanning several nights is required to derive one O–C point by comparing the current phasing to that of a mean model.

The EXOTIME program aims to increase the empirical data available on which to base such discussions.

5 The EXOTIME program

5.1 The planet-hosting pulsating sdB V391 Pegasi

V391 Pegasi (HS 2201+2610) was first discovered to be a rapidly pulsating subdwarf B star by Østensen et al. (2001b). Additional slow pulsations were subsequently reported by Lutz et al. (2009a). Silvotti et al. (2002a, 2007) were able to derive \( P \) values for the two strongest pulsation modes, and found an additional pattern in the observed–calculated (O–C) diagrams that revealed the presence of a giant planet in a 3.2 year orbit. The fact that this cyclic variation has been measured independently from two frequencies considerably strengthens the credibility of this discovery. Actually, Silvotti et al. (2007) detected parabolic and sinusoidal variations in the O–C diagram constructed for the two main pulsation frequencies at 349.5 s and 354.2 s over the observing period of seven years. The sinusoidal component with its 3.2 year periodicity is attributed to the presence of the very low-mass companion V391 Pegasi b at \( m \sin i = 3.2 \pm 0.7 \) M\( \text{Jup} \). The scenarios proposed for the origin of this planet are discussed in section 6.2.

5.2 Further characterization of V391 Pegasi system

The determination of the true mass of the "asteroseismic planet" V391 Pegasi b requires to find a constraint on the orbital inclination. Besides the orbital inclination, the orbit eccentricity has also not been well determined so far. The constraints on possible further planets are weak and currently allow for a second planet in the system massive enough to be detected. Continued photometric monitoring (on-going, see for example Fig. 2 Silvotti et al. in prep.) will be able to: check if the O–C evolves as predicted from the orbital solution, investigate the eccentricity, investigate a possible multiplicity, attempt another independent re-detection of the planet from \( P_3 \), and search for rotational splitting in the pulsations (see below).

As a first step to derive the mass of the known companion object with follow-up observations, Schuh et al. (2009) have attempted to determine the orbital inclination from spectroscopy. The approach suggested to achieve this is to use the stellar inclination as a primer for the orbital orientation. "Stellar inclination" can refer to the rotational or the pulsational axis, which as a further necessary simplification are assumed to be aligned, and can in turn then be derived by combining measurements of \( v_\text{rot} \) and \( v_\text{rot} \sin i \).
Fig. 3  Detail of the observed Hα core in a pulsation-integrated Keck spectrum of V391 Pegasi. The data (shown as a black line) are plotted centered on 6562.798Å. While measurements on the Hα core may be subject to systematic effects, this line is the only one available for such investigations in the spectral range covered by the observation. The flux was normalized; it does not reach unity at the edges of the plot as these regions are still well within the line wings. Overlay are 1) a model spectrum in red calculated from a NLTE pure H atmosphere model at $T_{\text{eff}} = 30\,000$ K and $\log (g/\text{cm} \cdot \text{s}^{-2}) = 5.50$, and 2) a model spectrum in blue from the same atmosphere model as before but rotationally broadened with 0.2 Å corresponding to 9 km s$^{-1}$.

The value for $v_{\text{rot}}$ is in principle accessible through rotational splitting in the photometric frequency spectrum (which has however not been found for V391 Pegasi yet), while the projected rotational velocity $v_{\text{rot}} \sin i$ can be measured from the rotational broadening of spectral lines. This rotational broadening must be deconvolved from the additional pulsational broadening caused by the surface radial velocity variation in high S/N phase averaged spectra.

Both phase averaged and phase resolved high resolution échelle spectra were obtained in May and September 2007 with the Hobby-Eberly Telescope (HET), and one phase averaged spectrum in May 2008 with the Keck 1 telescope, in order to put limits on the pulsational radial velocities. Échelle spectra of V391 Pegasi were taken during May and September 2007 with the HRS ($R = 15\,000$) of the HET at the McDonald Observatory, and with HIRES ($R = 31\,000$) at the Keck 1 telescope atop Mauna Kea in May 2008.

Using standard data reduction procedures, the individual échelle orders were merged and the final spectra carefully normalized and finally summed. This results in a set of individual spectra ($S/N \approx 3$), in particular two September 2007 high time resolution series, and summed spectra for May and September 2007 (Kruspe et al. 2008).

In an attempt to "clean" the relevant rotational broadening from pulsational effects, the spectra in September obtained in time resolved mode were combined to a series of ten phase resolved averaged spectra ($S/N \approx 9$) for the main pulsation period of 349.5 s (similar to Tillich et al. 2007).

The cross-correlation of this series of averaged spectra with a pure hydrogen NLTE model spectrum at $T_{\text{eff}} = 30\,000$ K and $\log (g/\text{cm} \cdot \text{s}^{-2}) = 5.5$ as a template yields pulsational radial velocity measurements for the different Balmer lines. The maximum amplitude of a sinusoidal curve (fixed at the expected period) that could be accommodated in comparison to the weighted means of the Balmer lines reveals that any pulsational radial velocity amplitude is smaller than the accuracy of our measurements and confirms the upper limit of 16 km s$^{-1}$ given by Kruspe et al. (2008).

The resolution of the model template matches the spectral resolution of the (pulsation-averaged) Keck spectrum. A comparison of the Hα NLTE line core shape (see Fig. 3) yields a more stringent upper limit for the combined broadening effect of pulsation and rotation of at most 9 km s$^{-1}$, meaning better spectral resolution and signal to noise data will be necessary to measure $v_{\text{puls}}$ and $v_{\text{rot}} \sin i$.

5.3 Exoplanet Search with the Timing Method

Following the serendipitous discovery of V391 Pegasi b, the EXOTIME\footnote{http://www.na.astro.it/~silvotti/exotime/} monitoring program was set up to search for similar systems. EXOTIME monitors the pulsations of a number of selected rapidly pulsating subdwarf B stars on time-scales of several years with the immediate observational goals of a) determining $\dot{P}$ of the pulsational periods $P$ and b) searching for signatures of sub-stellar companions in O–C residuals due to periodic light travel time variations, which would be tracking the central star’s companion-induced wobble around the centre of mass. The long-term data sets should therefore on the one hand be useful to provide extra constraints for classical astro-
seismological exercises from the $\dot{P}$ (comparison with “local” evolutionary models), and on the other hand allow to investigate the preceding evolution of apparently single sdB targets in terms of possible “binary” evolution by extending evolutionary models, and on the other hand allow to investigate the otherwise unsuccessful search for companions to potentially very low masses.

As noted before, timing pulsations to search for companions samples a different range of orbital parameters, inaccessible through orbital photometric effects or the radial velocity method: the latter favours massive close-in companions, whereas the timing method becomes increasingly more sensitive towards wider separations. A further advantage of timing versus radial velocities is that the former, although observationally expensive, is easier to measure than the latter. In fact, it is very hard to achieve the required accuracy in radial velocity measurements from the few and broad lines in hot subdwarf stars (a notable exception is the publication of small RV variations in the bright sdB HD 149382 as reported by Geier et al. 2009a.)

The targets selected for monitoring in the EXOTIME program are listed in Table 1. The target selection criteria applied to compile this list over time have been described by Schuh et al. (2010).

Table 1  Overview of the EXOTIME targets, see section 5 for details.

| target          | coordinates (equinox 2000.) | $m_B$ | status                      |
|-----------------|-----------------------------|-------|-----------------------------|
| HS 2201+2610    | 22:04:12.0 +26:25:07        | 14.3  | collecting data             |
| HD 0702+6043    | 07:07:09.8 +60:38:50        | 14.7  | collecting data             |
| HS 0444+0458    | 04:47:18.6 +05:03:35        | 15.2  | collecting data             |
| EC 09582−1137   | 10:00:41.8 −11:51:35        | 15.0  | collecting data             |
| PG 1325+101     | 13:27:48.6 +09:54:52        | 13.8  | collecting data             |

V391 Pegasi (HS 2201+2610) appears as the first entry, as the monitoring of this system is on-going (see §3). The rapid pulsations in HS 2201+2610 were discovered by Østensen et al. (2001b), and additional slow pulsations by Lutz et al. (2009a). An asteroseismology analysis of the star is included in Silvotti et al. (2002a 2007).

Rapid oscillations were discovered in the second target on the list, HS 0702+6043, by Dreizler et al. (2002), and simultaneous slow oscillations were reported by Schuh et al. (2006). The on-going EXOTIME observations for HS 0702+6043 have also previously been summarized by Lutz et al. (2008b 2009b), and include a significant contribution of data by Francœur et al. (2010).

The target HS 0444+0458 was first discovered to pulsate by Østensen et al. (2001a), and has been further characterized by Reed et al. (2007). EXOTIME has followed it regularly since 2008. Kilkenny et al. (2006) discovered rapid pulsations in EC 09582−1137 which Randall et al. (2009) subjected to an asteroseismology analysis. EC 09582−1137 is included in EXOTIME as a southern hemisphere target.

The discovery of pulsations in PG 1325+101 by Silvotti et al. (2002b) was also taken advantage of by characterizing the star asteroseismologically (Chapinet et al. 2006; Silvotti et al. 2006). This target is also extensively being observed within EXOTIME.

Schuh et al. (2010) present a portion of the observations currently available, describe the treatment of the data and display the first, still relatively short, O−C diagrams for the EXOTIME targets HS 0444+0458 and HS 0702+6043. Not surprisingly, these illustrate the need for further observations and interpretation. The analysis resorts to tools provided by Montgomery & O’Donoghue (1999) and Lenz & Breger (2005).

6 Sub-stellar companions of evolved stars

6.1 Post-main-sequence evolution

For single stars with initial masses below $\approx 2.2 \, M_\odot$ on the main sequence, the canonical steps in the evolution are: hydrogen shell burning following core hydrogen exhaustion, core mass increase (due to the shell burning) and core contraction with increasing electron degeneracy simultaneous to radius swelling on the first giant branch (RGB), ended by onset of a core helium flash, which brings the star onto the horizontal branch. Their masses now lie in the range roughly $0.5 \, M_\odot < M < 1.0 \, M_\odot$, with a canonical core mass of $0.46 \, M_\odot$ and variable envelope masses with or without hydrogen shell burning that determine the location on the horizontal branch. The hottest, bluest objects are the least massive and have thin envelopes that put the most extreme of these objects with inert hydrogen shells on the EHB. This sequence is terminated at the point where the helium main sequence coincides with the horizontal branch helium core mass.

After core helium exhaustion the complex asymptotic giant branch evolution with H and He shell burning, thermal pulses, convection and dredge-up processes, and extreme mass loss unfolds. The subsequent post-AGB phase sees the creation of a planetary nebula from the envelope material lost and the emergence of the stellar remnant on its way to the white dwarf cooling track.

As the subdwarf B stars are in between the RGB and AGB giant expansion phases, or more precisely, will not undergo AGB evolution, their observation allows to separate the effects of the first giant branch on planets from those of the asymptotic giant branch.
Fig. 4  The subdwarf B (sdB) star V391 Pegasi oscillates in short-period p modes and long-period g modes, making it one of the known hybrid pulsators among sdBs. As a by-product of the effort to measure secular period changes in the p modes due to evolutionary effects on a time scale of almost a decade, the O–C diagram has revealed an additional sinusoidal component attributed to a periodic shift in the light travel time caused by a planetary-mass companion around the sdB star in a 3.2 year orbit. In the above artistic impression, the V391 Pegasi system is shown at an earlier evolutionary stage in one of the proposed scenarios where, roughly $10^8$ years ago, the star, at maximum red giant expansion, almost engulfed the planet. © Image courtesy of HELAS, the European Helio- and Asteroseismology Network, funded by the European Union under Framework Programme 6; Mark Garlick, artist.
6.2 The fate of planets around evolving stars

The starting point of discussions on planets around evolved stars is often that relic planets around white dwarfs are expected simply due to the considerable number of planets found around main sequence stars. The question then is at what initial masses and orbital separations the planets actually can survive both giant expansion phases of their host star without being engulfed, disrupted, evaporated or ejected. Debes & Sigurdsson (2002) consider the effects of mass loss, planet-planet interactions, and orbit stability and conclude that while inner planets will perish, far-out small bodies and distant planets have the potential to create a new dust disk. Such as disk could then pollute the central white dwarf’s atmosphere to create a DAZ, and be observable via its IR excess. – While the search for planets around single white dwarfs has not been successful yet, the existence of dusk disks has indeed been established observationally.

In addition to orbital effects, Villaver & Livio (2007) consider the thermal conditions during the planetary nebula phase and establish new regions in the orbit and mass parameter space where planets survive all the way to the white dwarf stage of their host stars. Focusing more on the orbital evolution, Haghighipour (2008) investigates the issue of survival for planets in binary systems. A consequence in all of these studies is that finding planets at parameter combinations that correspond to previously “forbidden regions” immediately requires that second generation planet formation scenarios must have been at work. This can in principle include migration and significant accretion of previously existing planets in newly formed disks.

Of course, these investigations are predominantly concerned with the more violent effects during the AGB phase. However, once a planet has made it safely into the orbit of a subdwarf B host star, it can be expected to continue to exist without too much hassle when the host evolves to its final white dwarf stage.

A first scenario that explained the case of V391 Pegasi b basically in the context of single star evolution assumes that the planet is an old first generation planet which survived a common envelope phase. The situation where the star at maximum red giant expansion almost engulfed the planet is depicted in Fig. 6.2. Assuming this scenario, the existence of V391 Pegasi b proves observationally that gas-giant planets can survive the first red giant expansion in orbits similar to that of our Earth. Silvotti (2008) puts forward alternative scenarios. In a second variant, V391 Pegasi b would have been an outer planet, never really under a strong direct influence of the expanding host star. The exceptional mass loss of the host star, turning it into a sdB, would instead have been triggered by another closer-in planet that got potentially destroyed in the process.

Scenario three explains V391 Pegasi b as a young second generation planet formed in a disk resulting from the merger of two He white dwarfs. The planet would then be a helium planet (compare also Livio et al. 2005).

In the case of the planets around HW Vir-like systems, the situation is somewhat easier as there is no dispute about the origin of the enhanced mass loss in a common envelope ejection phase. Besides the argument by Lee et al. (2009) that the planets were formed in a circumbinary disk, this leaves room for an interesting variety of possible planet formation scenarios, including a second generation scenario (cited from Heber 2009): “At birth, HW Vir’s binary components must have been much further apart than they are today. During this [red giant] mass-loss episode the planets as well as the stellar companion may have gained mass. Rauch (2000) suggested that the low-mass companion in AA Dor may have grown from an initial planet by mass accretion during the CE-ejection phase. Could that have happened to the HW Vir system? As a matter of pure speculation, the star may have been born with three massive planets: the innermost launched a CE ejection, spiraled in, and accreted so much material as to turn into a low-mass star. […] Another speculation concerns in situ formation; that is, could the planet have been formed during the CE phase?”

6.3 The fate of evolving stars with planets

As already implied above, it has recently been suggested that the presence of planets may have implications for the formation of sdB stars. This marks the renaissance of an older idea: Soker (1998) suggested that planets may constitute the second parameter influencing the irregular morphology of the (blue part of the) horizontal branch in globular clusters and elliptical galaxies. The physical processes discussed as candidates for the second parameter in horizontal branch morphology are

- age of the globular cluster,
- deep helium mixing and radiative levitation,
- large He abundance or fast rotation,
- stellar density in the cluster,
- planets enhancing mass loss on the red giant branch.

Quite similarly to this last suggestion (Soker 1998), Soker (2010) points out that in addition to strengthening the blue component of the normal horizontal branch, enhanced mass loss due to planets could also be decisive in forming subdwarf B stars. The initial prediction – that the engulfed planet that helps to shed the envelope will in most cases be destroyed in the process – remains valid, so this hypothesis is challenging to test.

However, V391 Pegasi, while most probably not capable to have caused the enhanced mass loss of its host star itself, may well be regarded as a possible tracer for (former?) inner planets that could indeed have been able to cause the amount of mass loss required (compare the second scenario in the previous section). The scenario as a general explanation for the formation of a significant part of the single sdB star population may have a number of unsolved problems, mostly related to our poor understanding of the common envelope ejection mechanism. But, independently of the theory, EXOTIME and other programs now start to built up an empirical data base of low-mass companion statistics that further discussions can be based on. This should
help to clarify the role of an – to date perhaps mostly still undiscovered – population of very low-mass companions to apparently single subdwarf B stars in the formation of these objects.

Should it one day become possible to determine the composition of the low-mass objects found, and should these turn out to be planets that were most likely formed in the helium disk of a He white dwarf merger event, the origin of the host stars will also have been cleared up unambiguously.

7 Summary

This article has attempted to highlight the added value of incorporating stellar pulsations in the comprehensive investigation of various stellar and planetary systems.

The potential of links between asteroseismology and exoplanet science was first illustrated for solar-like oscillators. Accurate asteroseismic radii for (solar-like) host stars of transiting exoplanets translate into good radius determinations for the transit planets.

In the context of connections with coherent pulsations, as found in evolved stars, the focus was directed towards the investigation of stellar and planetary systems at late stages of stellar evolution. The asteroseismology-exoplanet-connection was explored in particular for post-RGB stars. The exotic class of subdwarf B stars, of which many show pulsations, was introduced as a group with several new planet discoveries. In discussing the fate of planetary systems based on known planets around extreme horizontal branch stars (e.g. V391 Pegasi), the question arises whether these are first or second generation planets. Data from programs such as EXOTIME, which make use of the timing method to find more such systems, can fill a gap with respect to the sensitivity to planets in wide orbits and applicability to evolved stars.

With respect to the puzzle of subdwarf B formation, planets were proposed to (partly) be at the origin of subdwarf B stars, and also to play a role as the second parameter for the horizontal branch morphology in globular clusters and elliptical galaxies.

The aspects this article summarizes are all from the pre-
Kepler era. It will be fascinating to see how our understanding in a great many areas evolves with the new data.

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