Close-in planets around sdB stars

A step toward constraining their masses ?

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In Charpinet et al. (2011), we presented first evidence of the presence of a very compact planetary system orbiting the sdB star KIC 05807616. The configuration of the system and the estimated radii for the planet candidates suggested that these nearly earth-size objects could be the remnants of one or more giant planets engulfed and partially disrupted in the expanding envelope of the former red giant star. In this scenario, only their dense core would have survived the event, leaving the small objects that we see. Testing further this hypothesis would require a mean to constrain the masses of the planet candidates in order to estimate their average densities. In this work, we introduce an interesting new approach that could potentially fulfill this objective.

Introduction

The detection of weak periodic signatures at low frequencies in the lightcurve of the sdB star KIC 05807616 (a.k.a. KOI 55 or Kepler 70) led Charpinet et al. (2011) to the conclusion that two small earth-size planets (and possibly a third one) are orbiting very close to this star. This finding has profound implications as it suggests that planets could both survive, at least partially, immersion into red giant envelopes and play a role in the envelope ejection leading to the formation of sdB stars. In this context, Charpinet et al. (2011) and Bear et al. (2012) proposed that the small detected objects could be remnants of the core(s) of former giant planet(s) swallowed and partially disrupted (see Silvotti et al. 2014 for a similar case reported recently). This scenario would imply that the planet candidates are dense objects, thus relatively massive for their size. Unfortunately, radial velocity measurements are not currently feasible to test further this idea, but there might be other ways that we explore below.

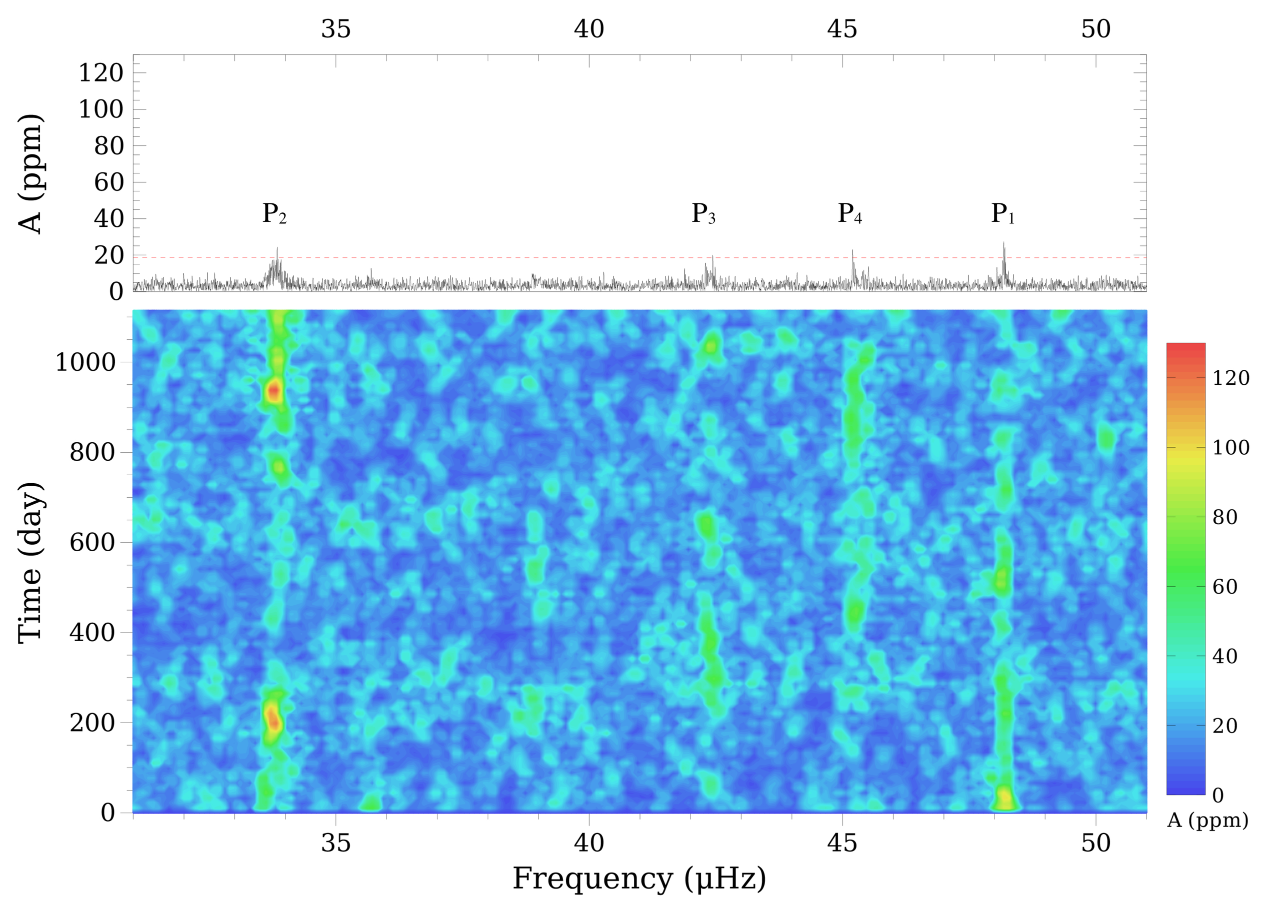

Figure 1 – Analysis of 1115 days (Q5 to Q16) of short cadence *Kepler* photometry obtained on KIC 05807616, with a close-up view of the 32 – 49 μHz frequency range where planetary signatures are found. *Top panel*: High resolution Lomb-Scargle periodogram of the full lightcurve. The red dotted line indicates the secure detection threshold (5.6σ; see **Figure 2**). *Bottom panel*: Time-Frequency diagram built from sliding Lomb-Scargle periodograms using a 56 day wide window moved by steps of 11 days along the lightcurve.

Two main peaks (P1 and P2) emerge well above the detection limit and correspond to the 2 planets reported in Charpinet et al. (2011). Two additional structures (P3 and P4) also reaches the threshold and could be considered as real signal with some reasonable confidence. These suggest the presence of 2 more orbiting objects, noting that P3 had already been mentioned in Charpinet et al. (2011). In addition, it appears that the orbital frequencies are not perfectly stable over time as one would expect for a pure unperturbed circular orbital motion. We interpret these frequency modulations as indicative of mutual gravitational perturbations occurring between the planets of the system.

We also point out that amplitude variations are noticeable in the time frequency diagram but are mostly due to noise fluctuations (see the discussion in the main text and **Figure 4**).

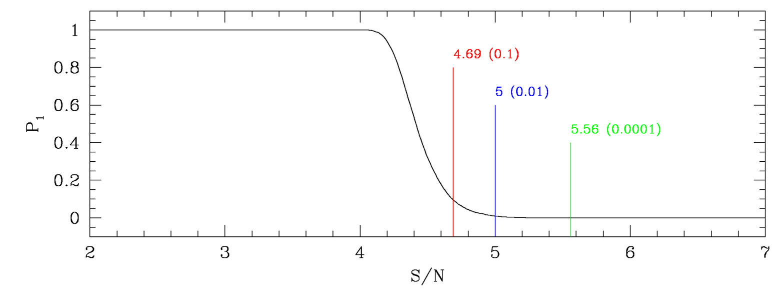

Figure 2 – Probability that a peak above a given S/N threshold is due to noise fluctuations. This probability has been estimated by computing the Lomb-Scargle periodograms of 10,000 synthetic lightcurves just containing random Gaussian noise and using the exact same time sampling as the *Kepler* observation of KIC 05807616. We adopt as a secure detection threshold the limit where this false detection probability goes below 1 chance over 10,000 (0.0001), which occurs at 5.6σ.

Planet id.	P_1	P_2	P_3	P_4
Orbital parameters (Figure 1) :				
Frequency (μHz)	48.1824 ± 0.0007	33.8423 ± 0.0008	42.4375 ± 0.0010	45.1987 ± 0.0008
Period (s)	20754.5 ± 0.3	29548.9 ± 0.7	23564.0 ± 0.5	22124.5 ± 0.4
Resonance P_2/P_n	7:5	1	5:4	4:3
Amplitude (ppm)	27 ± 3	24 ± 3	20 ± 3	23 ± 3
S/N	8.2σ	7.3σ	6.0σ	6.9σ
Main planetary parameters used in the representative simulation (Figure 4) :				
Radius ($R_\oplus$)	0.70	0.84	0.61	0.57
Mass ($M_\oplus$)	0.11	0.22	0.08	0.09

Table 1 – Orbital parameters deduced from the analysis of the data (**Figure 1**) and planet's radii and masses used in the simulation shown in **Figure 4**.

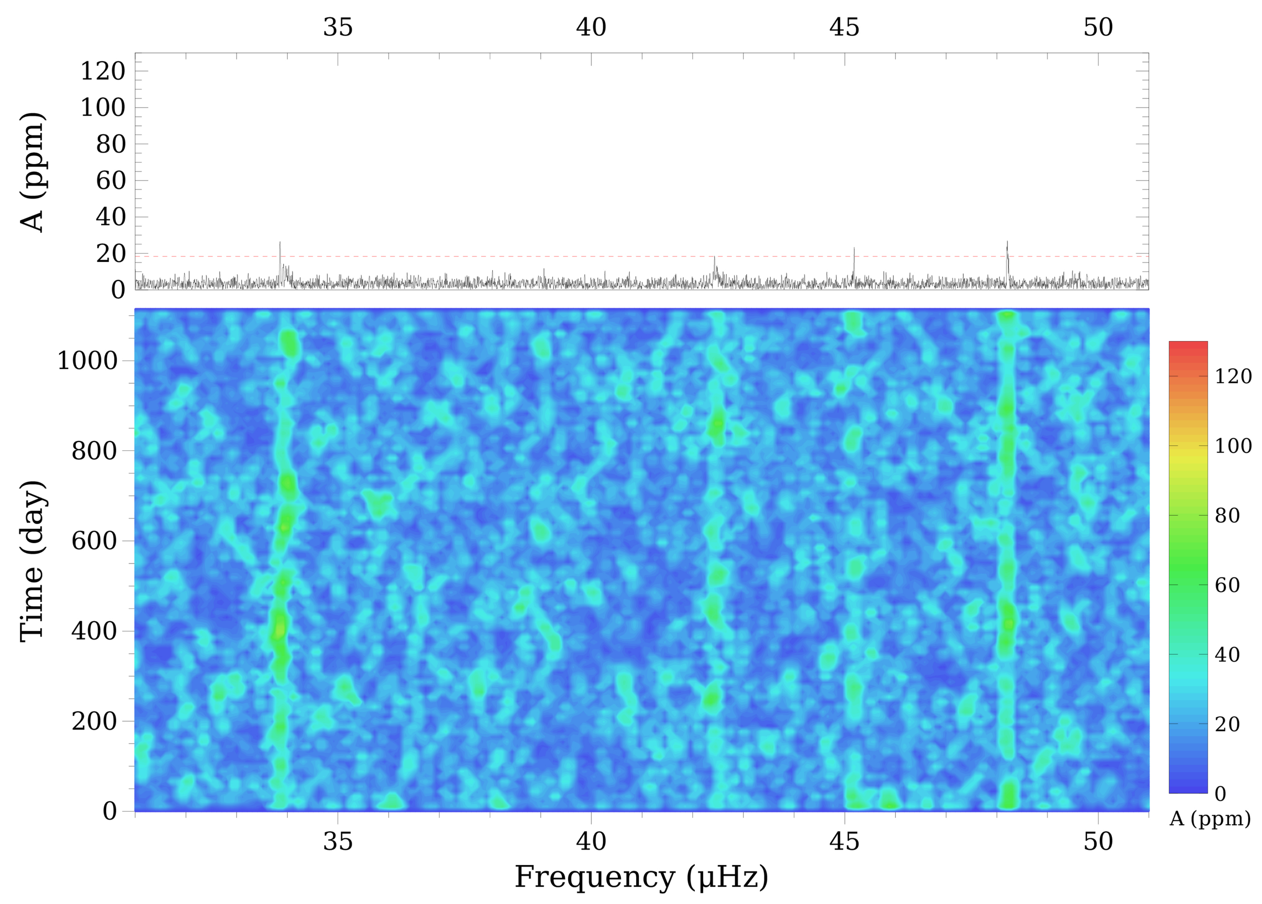

Figure 4 – Simulated data that roughly mimic the real data presented in **Figure 1**. This simulation covers 1115 days with a sampling time of 60 s and includes Gaussian white noise of the same level as in the *Kepler* observation. In this example, the radii of the 4 suspected planets were adjusted to produce peaks of amplitudes comparable to the observed ones (within the model framework discussed in Charpinet et al. 2011). The masses were chosen to produce mild perturbations leading to the frequency modulations. The adopted values are summarized in **Table 1.** Of course we stress that these are just representative values and by no mean the result of an objective determination of these parameters. We point out that in this specific simulation we postulate the presence of a 5th planet of 0.12 earth mass beyond the orbit of P2 in order to produce perturbations comparable to those seen in the real data for that specific object.

While this simulation does not pretend to reproduce exactly the configuration of KIC 05807616 (as this would require a thorough exploration of various configurations within an extremely vast model parameter space), it clearly features similarities with the observed signatures and demonstrates the viability of this interpretation.

Signature of mutual gravitational perturbations in KIC 05807616 / Lightcurve simulations

KIC 05807616 forms a very compact planetary system in which one would expect mutual gravitational perturbations to occur, thus affecting the orbits in a complex manner. Such perturbations have indeed been observed in many *Kepler* systems through, e.g., the Time Transit Variations (TTVs; Mazeh et al. 2012), sometimes even leading to discoveries of new formerly unseen planets betrayed only by their gravitational influence (Ballard et al. 2011). In our case, the perturbations would manifest themselves primarily as small variations of the orbital periods (i.e., the same effect leading to TTVs), and consequently as frequency modulations of their photometric imprint over the observation time baseline (we recall here that these planets are detected through the orbital modulation of the light reflected and thermally re-emitted at their surface). Charpinet et al. (2011) already pointed out the possible presence of such modulations in KIC 05807616 based on 14 months of Kepler data available at that time. We reconsider here the question with all the data (more than 3 years of nearly continuous photometry).

Figure 1 shows a close up view of the frequency range where the planetary signatures are found. With the full data set, it turns out that 4 signatures (P1 to P4) now emerge above the detection threshold (see **Figure 2** for details on how this threshold is estimated), pointing toward the presence of 4 small orbiting objects. **Table 1** gives some of the orbital properties that can be deduced from the analysis of the *Kepler* light curve (In particular we note that resonance relations seem to connect one of the planets (P2) to the 3 others).

Figure 3 shows the result of light curve simulations based on a N-body integrator (REBOUND; Rein & Liu. 2012) modified to incorporate the simple reflection and thermal re-emission model described in Charpinet et al. (2011). The evolution of a system with 4 planets that could be representative of KIC 05807616 was computed assuming different planetary masses (from a system with no gravitational perturbation to a system that becomes dynamically unstable). **Figure 4** shows a simulation including noise adjusted to roughly reproduce the observed signatures. This test demonstrates that signatures similar to those seen in **Figure 1** can indeed be obtained as a result of mutual planet interactions within the system.

From these numerical experiments, we find that the effect of mutual gravitational perturbations between the planets have the following signatures :

<u>Frequency modulations</u> : The perturbations indeed generate complex variations affecting in particular the orbital periods (frequencies). In Fourier space, this translates into frequency modulations that can induce enlarged or muti-peak signatures that depends on the magnitude of the perturbations.

<u>Amplitude modulations</u> : The perturbations can also generate amplitude modulations in a sliding Fourier spectrum due to variations in the frequency modulation pattern occurring within each time window. However, in the present case, the dominant source of apparent amplitude variation is simply due to the low signal-to-noise of the detections making them quite sensitive to random noise fluctuations (as is clearly seen in **Figure 1** and **4**). We note that a third source of amplitude modulations could also be intrinsic to the observed objects, since significant evaporation of the planets is expected to occur in such a system. This effect could induce light variations that however have yet to be quantified.

Prospects for determining the planet masses : The frequency modulations generated by the gravitational perturbations depend on the masses of the orbiting bodies. Therefore, these could in principle be constrained by matching simulations to the observed signatures. Combined with fitting the amplitude of the peaks, which is a strong function of the planetary radius (given a reflection/reemission model), this could lead us to derive interesting constraints on the mean density of these objects, a key information for testing their nature and origin.

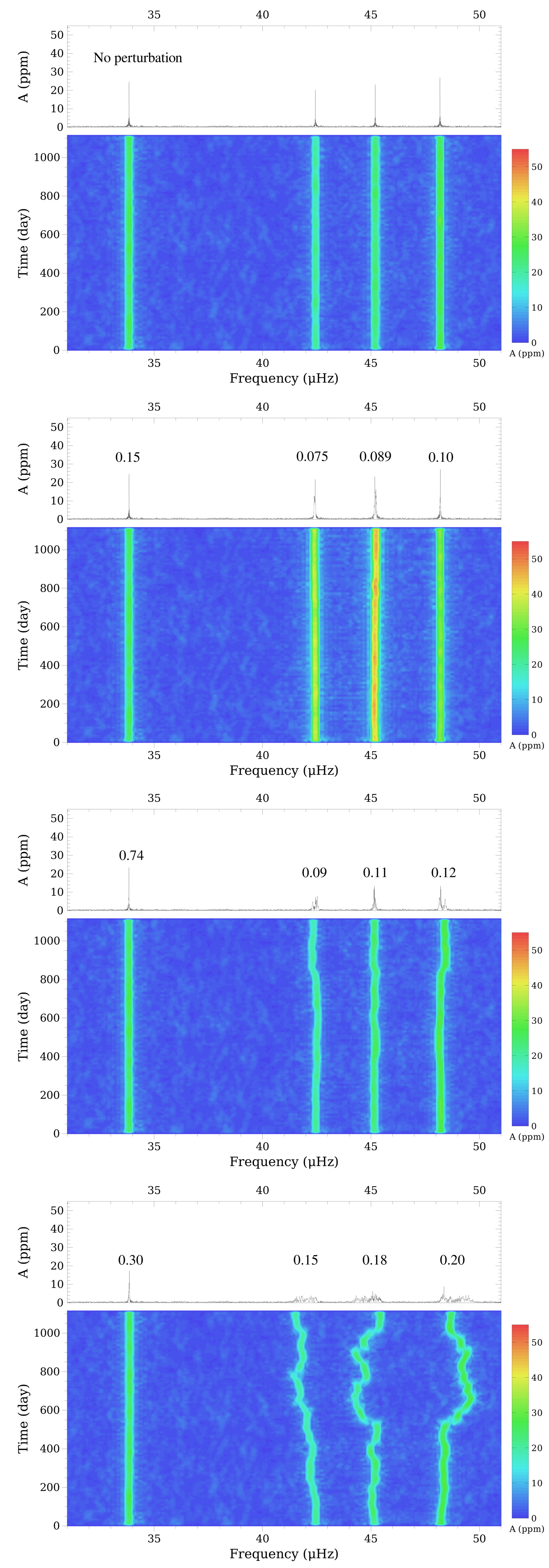

Figure 3 – Analysis of simulated low noise lightcurves computed with the N-body integrator REBOUND (Rein & Liu, 2012) for a configuration of 4 planets with different masses (the values, in earth mass, given above each peak). The simulations cover 1115 day with a sampling time of 60 s (hence similar to the available *Kepler* data). The top panel represents the case with no gravitational perturbation (purely periodic orbits) and mass is globally increased from top to bottom, up to a case where the system becomes dynamically unstable.

Références : Ballard et al. 2011, *ApJ*, **743**, 200 ; Bear et al. 2012, *ApJ*, **749**, L14 ; Charpinet et al. 2011, *Nature*, **480**, 496 ; Mazeh et al. 2012, *ApJS*, **208**, 16 ; Rein, H & Liu, S.-F. 2012, *A&A*, **537**, 128 ; Silvotti et al. 2014, *A&A*, **570**, 130