Kepler Observations of Pulsating Subdwarf B Stars

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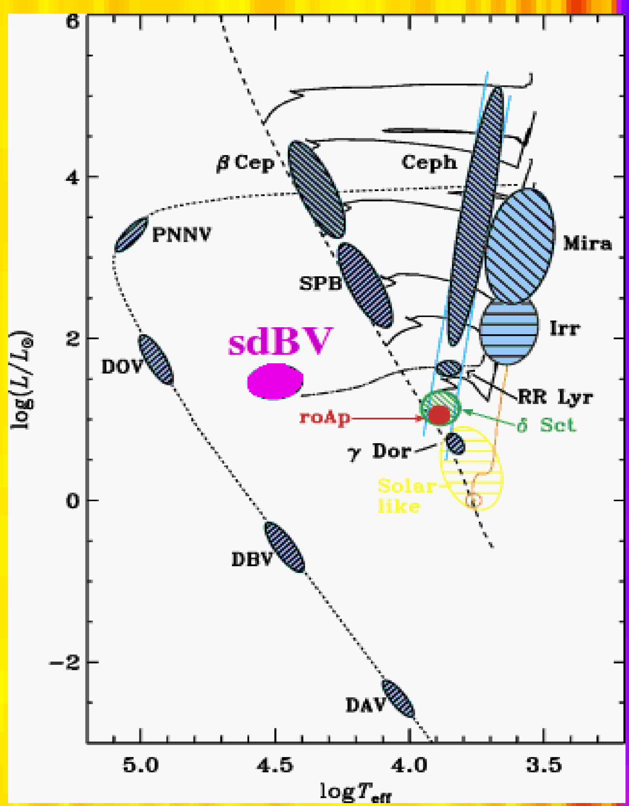

Figure 1: Pulsating stars in the HR diagram. Originally created by J. Christensen-Dalsgaard, now modified.

ABSTRACT

Kepler observations of pulsating subdwarf B (sdBV; also known as extended horizontal branch) stars have presented a revolution in compact seismology. Prior to Kepler observations, the models were relatively unconstrained by observations because of a lack of mode identifications. Now, from extended Kepler observations, we have several means to observationally constrain the mode identification as well as time-dependent examinations of the pulsation amplitudes and frequencies. Kepler has discovered 18 sdBV, nearly all of them *g*-mode pulsators with periods of a few hours. *p*-modes have periods of a few minutes and several of the stars are hybrid pulsators. Rather than provide KIC numbers, I have used the nicknames some within WG11 use.

Period Spacings

It was noticed during the survey phase that the periods in sdBV stars surprisingly follow the asymptotic relations for *g*-mode pulsations (Reed et al. MNRAS, 2011). This was unexpected as it was anticipated that internal differentiation would not allow it (talk by Charpinet on Thursday). The asymptotic relationships provide relationships between modes of the same and different *l* values, So far, only *l*=1 and 2 modes have been identified in this manner. The period spacings have values near 250 and 145 seconds for *l*=1 and 2 modes, respectively. Figure 2 shows period spacings discovered in Bilbo from a month of Quarter 2 data.

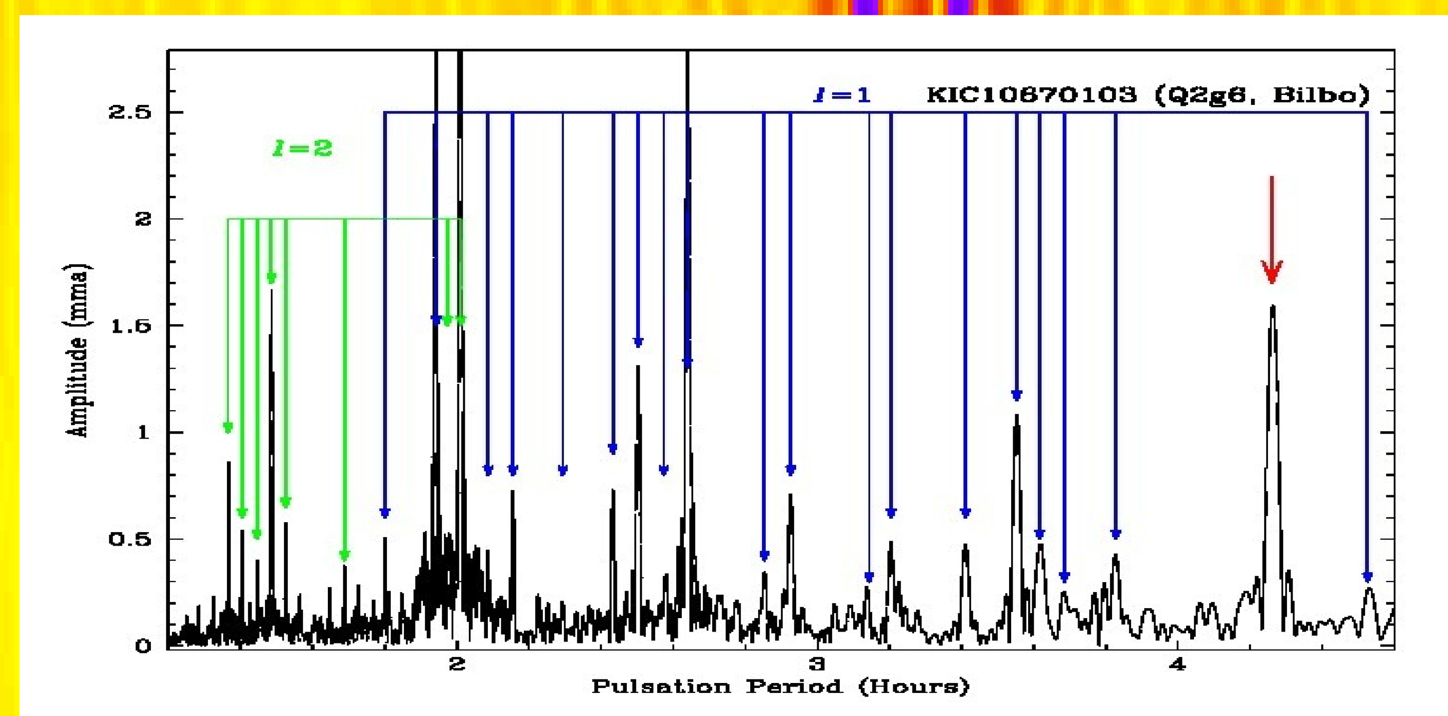

Figure 2: A period transform showing the *l*=1 and 2 period spacing sequences from Q2M1.

Name	P_{spin}(d)	P_{orb}(d)	Reference
Saradoc	25.6	-	Baran et al. 2012a
Mungo	45	10.05	Telting et al 2012
Pippin	45	-	Baran et al. 2012b
Merry	10.46	0.44	Baran & Winans 2012
Rorimac	7.2	0.40	Baran & Winans 2012
Adamanta	9.6	0.40	Baran & Winans 2012
Bilbo	88	-	Reed et al. 2013
Largo	96.5	-	Ostensen et al. 2012
Samwise	32	-	Foster et al. 2013

Frequency Multiplets

From extended Kepler observations, frequency multiplets have been discovered in most of the stars examined to date (see the papers of Baran et al. 2012). Frequency multiplets follow the relations $\Delta\nu = m\Omega(1-C_{n,l})$ where *m* is the azimuthal value which can have 2*l*+1 integer values and $C_{n,l}$ is the Ledoux constant which for *g*-modes takes on values near $C_{n,l}$<1/[*l*(*l*+1)] and so depends on the mode. In this manner, both the number of peaks observed (i.e. triplets or quintuplets) *and* the spacing between them (which depends on $C_{n,l}$) provide mode identifications. Examples of Fourier transforms with multiplets are shown in Figure 3. From these multiplets, we have learned that sdB stars are slow rotators. Even when in binaries, they are not likely to be tidally locked (see papers by Pablo & Kawaler 2012 and references listed in the table.) This explains why multiplets were rarely observed from ground-based data.

Sliding Fourier Transforms: Time resolution of pulsations.

Because of Kepler's unique nature of continually observing stars over several years, we can examine how *resolved* multiplets evolve with time. We do this by using spans of data which are 50% longer than required to resolve the multiplets, and then advancing them from the first data point by a few days, until the last data point is reached. In nearly all cases analyzed so far, amplitudes vary dramatically and occasionally frequencies vary too. This level of detail into the pulsation power structure of pulsating stars has never before been seen, except possibly in our Sun. We hope that in time, pulsation theory will be able to model the detail we can already extract from Kepler data.

Kepler data also provide a challenge: How should data be analyzed when from the sliding FT, it is obvious that not all components of a multiplet occur simultaneously or have large amplitude and/or frequency variations? (See figures at bottom left and bottom right.) The traditional method of non-linear least squares fitting and prewhitening no longer works. We would very much like to know what solutions others have found or simply to get suggestions on how to proceed ourselves.

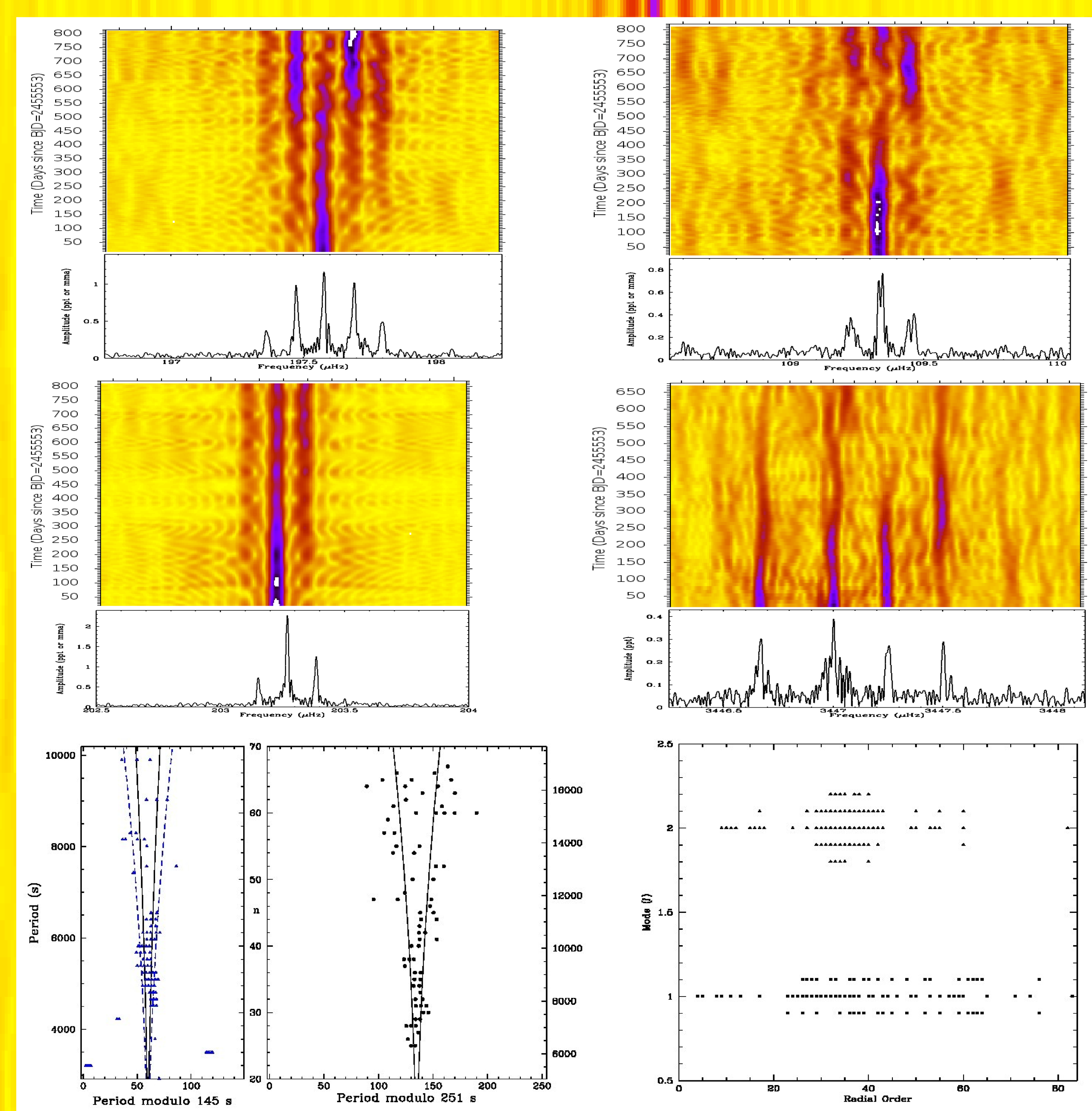

Figure 3: The top two panels show sliding FTs along with the corresponding FTs of the entire data set. The bottom panels show *l*=1 and 2 modes with radial order. The structure between n=30 and 45 may be used to constrain the H/He transition zone.

Results

Accomplishments derived from Kepler observations of sdBV stars so far include: • 60-70% of periodicities have been identified as *l*=1 or 2 modes. • Mode identifications can be made using three methods: 1) Period spacings, 2) frequency multiplets, and 3) the separation of the frequency multiplets using differing Ledoux constant values. • Spin periods have been determined and it has been discovered that these are not tidally locked, even in short period binaries. • Relativistic beaming has been observed and analyzed (Telting et al 2012) • We have been able to observe time-dependent frequency/amplitude changes.

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