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Finding non-eclipsing binaries through pulsational phase modulation

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Abstract. We present a method for finding binaries among pulsating stars that were observed by the *Kepler* Mission. We use entire four-year light curves to accurately measure the frequencies of the strongest pulsation modes, then track the pulsation phases at those frequencies in 10-d segments. This produces a series of time-delay measurements in which binarity is apparent as a periodic modulation whose amplitude gives the projected light travel time across the orbit. Fourier analysis of this time-delay curve provides the parameters of the orbit, including the period, eccentricity, angle of ascending node and time of periastron passage. Differentiating the time-delay curve yields the full radial-velocity curve directly from the Kepler photometry, without the need for spectroscopy. We show examples with delta Scuti stars having large numbers of pulsation modes, including one system in which both components of the binary are pulsating. The method is straightforward to automate, thus radial velocity curves can be derived for hundreds of non-eclipsing binary stars from Kepler photometry alone.
This contribution is based largely upon the work by Murphy et al. [1], describing the phase-modulation method in detail.

1 Introduction

The study of binary stars in an asteroseismic context is essential to our understanding of stellar structure and evolution. Asteroseismology offers information on the stellar interior, while eclipsing binaries in particular provide constraints on the fundamental stellar parameters mass and radius. The importance of pulsating stars in binaries is widely recognised (e.g. [2,3]) but most efforts so far have been limited to eclipsing systems (e.g. [4–9]).

Even in the non-eclipsing case, the binary parameters can be determined. The orbital motion of a star in a binary system leads to a periodic variation in the path length travelled by the light that we observe. Hence, the phase of an observed 'clock' varies over the orbit. The clock most often adopted is the constant frequency of absorption lines in the stellar spectrum. Then the variation in those spectral lines, as measured with high-resolution instruments at large ground-based telescopes, provides radial velocity measurements. Obtaining the required telescope time at the appropriate orbital phases places a bottleneck on the process. Yet it is not necessary to use spectral lines – any clock will do, and the clock we use here is that of the fixed frequencies of coherent stellar oscillations (e.g. [10–13]), which we obtain from the almost uninterrupted, 4-yr datasets provided by *Kepler* in long-cadence (LC) mode (30-min sampling).

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Shibahashi & Kurtz [14] showed that the light-time effect in a binary star leads to frequency modulation (FM) of pulsation frequencies. This generates multiplets in the Fourier transform of the stellar light curve, from which the binary parameters can be determined.

Murphy et al. [1] developed a complementary method summarized here, by which we extract explicitly the phase modulation (PM) in the time domain of intrinsic pulsation frequencies of the star, which is caused by binary orbital motion. We exploit this to derive the orbital radial velocities and the other orbital elements from the light curve alone. An advantage of this PM method, compared to the FM method, is that it provides the variation in the light-travel time at short intervals. This is particularly useful in visualizing the variation caused by the binary motion, and its time derivative provides the radial velocity. Furthermore, the signals from different pulsation modes in multiperiodic stars can be combined. All of this is straightforwardly automated. Unlike the traditional O–C (observed minus calculated) method, PM uses all of the data – not just the pulsation maxima – and is particularly suited to multimode pulsators. The validity of FM and PM has been confirmed with known binaries ([15], [16]).

2 Phase Modulation Method

We obtained the stellar oscillation frequencies from Fourier transforms of 4-yr datasets of *Kepler* δ Sct stars, optimised with a non-linear least-squares algorithm. We then divided the light curve into short segments and calculated the phase of each of the (fixed) frequencies in each segment. The observed phase variations induced by the binarity have frequency dependence, hence we convert them into light arrival times, which we refer to as time delays. The measured time delay, τ, for frequency ν_j in segment i is related to the phase shift with respect to the mean $\Delta\phi_{ij}$ by

$$\tau_{ij} = \frac{\Delta\phi_{ij}}{2\pi\nu_j}. \tag{1}$$

For a binary in a circular orbit, the time delays for each ν_j follow a sinusoid whose period is the binary period and whose amplitude is the projected light travel time across the semi-major axis. These two parameters are obtained from a Fourier transform of the time delays. The derived parameters have their smallest uncertainties when the weighted-average time-delay is taken, using the phase uncertainties as weights. In the non-circular case, a Fourier series is seen at the orbital frequency in the Fourier transform, from which the eccentricity is approximated as twice the amplitude ratio between the peaks at $2\nu_{\rm orb}$ and $\nu_{\rm orb}$, i.e.

$$e \approx 2A(2\nu_{\rm orb})/A(\nu_{\rm orb}). \tag{2}$$

All of this can be automated, making the search for binaries stars efficient. An example is shown in Fig. 2.

A radial velocity curve can be computed from the time delays, using eq. 7 from [1]:

$$v_{\rm rad,1}(t) = -c\frac{{\rm d}\tau}{{\rm d}t}. \tag{3}$$

The phased RV curve computed for the example used in Fig. 1 (KIC 9651065) is shown in Fig. 2. All the information required to derive the full binary parameter set can be found in [1].

Both the PM method and the FM method give the same information, but in different ways. The FM method is superior for short orbital periods, where the need to go to progressively shorter segments causes resolution problems in the PM method. On the other hand, the automation, visualisation and multi-mode treatment of PM lends itself to large samples of stars. It also picks out binaries where both stars pulsate, such as KIC 4471379, whose time delays are shown in Fig. 3. We obtained a spectrum of this binary with the FIES spectrograph ([17]) at the Nordic Optical Telescope in service mode on 2014-07-14. Given the system's orbital period and the availability of the *Kepler* field, a spectrum could not be obtained at quadrature. Our spectrum at conjunction is unable to detect the double-lined nature of the binary because the lines are superimposed. Thus the PM method, which predicts a mass ratio > 0.95, can outperform even high-resolution spectroscopy in detecting some binaries due to its long baseline and near-continuous coverage.

Fig. 1. (a): Fourier transform of the light curve of KIC9651065. The dashed line is the *Kepler* LC Nyquist frequency. (b) Time delays for the nine highest peaks, using 10-d segments. Nyquist aliases are excluded using the super-Nyquist asteroseismology method ([18]). (c) Fourier transforms of the time delays for those nine peaks; all show variability at the binary orbital frequency $\nu_{\rm orb} = 0.00367\,{\rm d}^{-1}$. (d) Fourier transform of the weighted-average time-delays. The orbital frequency and two harmonics, which have amplitudes of $A_1 = 165.6$, $A_2 = 38.4$ and $A_3 = 10.2$s (±2s), were obtained from least squares fitting. The inferred eccentricity is $e = 0.46$.

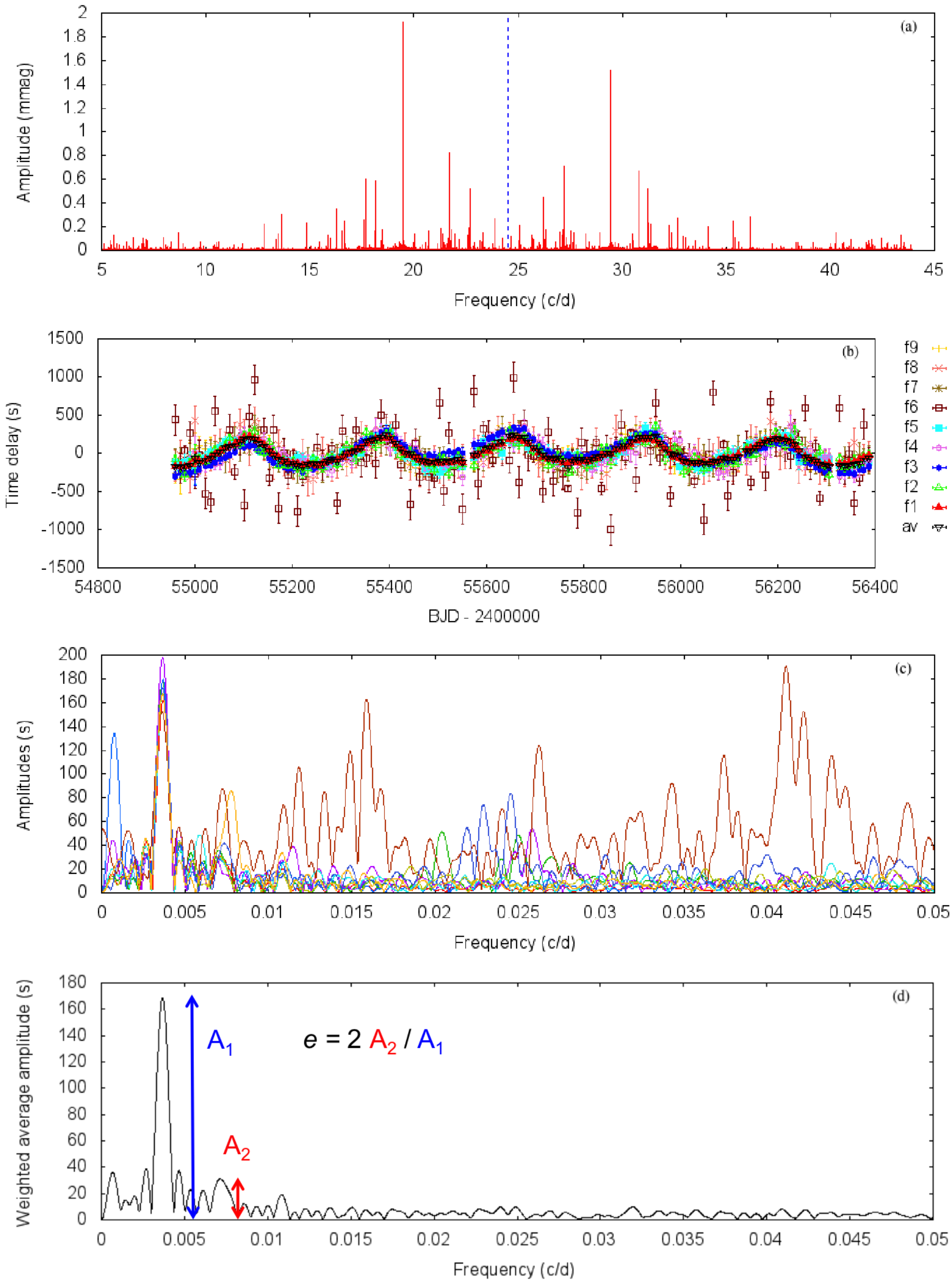


Fig. 2. Phased RV curve for KIC9651065, whose time delays were shown in Fig. 2. Green circles represent individual RV measurements, and the black curve is the fit obtained using analytical functions described in [1].

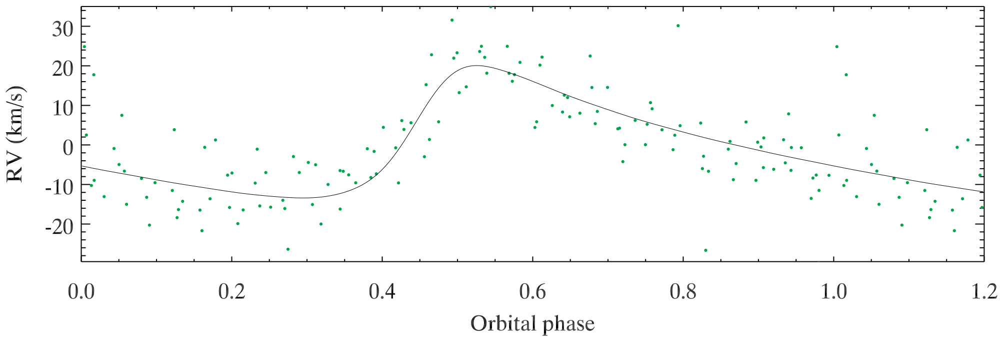
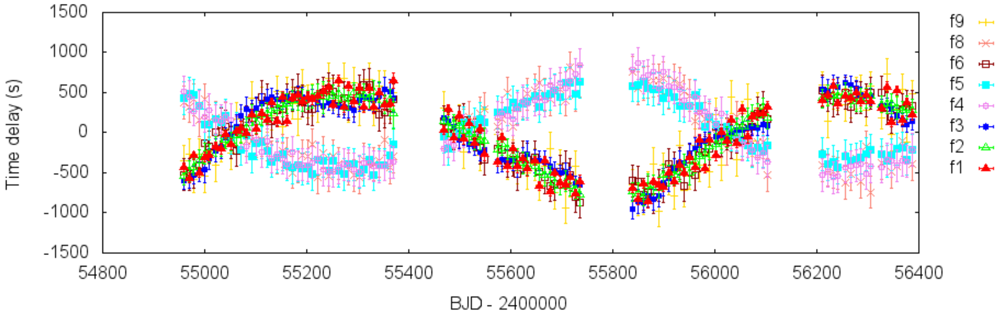


Fig. 3. Time delays for KIC4471379 – a binary with two δ Sct stars. Time delays show two pseudo-sinusoids with equal periods and opposite phases.



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