Finding binaries from phase modulation of pulsating stars with *Kepler*

Hiromoto Shibahashi[1,⋆], *Simon* Murphy[2,3,⋆⋆], and *Tim* Bedding[2,3,⋆⋆⋆]

[1] *University of Tokyo, Department of Astronomy, Tokyo 113-0033, Tokyo, Japan*
[2] *University of Sydney, Sydney Institute for Astronomy, NSW 2006, Australia*
[3] *Aarhus University, Stellar Astrophysics Centre, DK-8000 Aarhus C, Denmark*

Abstract. Binary orbital motion causes a periodic variation in the path length travelled by light emitted from a star towards us. Hence, if the star is pulsating, the observed phase of the pulsation varies over the orbit. Conversely, once we have observed such phase variation, we can extract information about the binary orbit from photometry alone. Continuous and precise space-based photometry has made it possible to measure these light travel time effects on the pulsating stars in binary systems. This opens up a new way of finding unseen brown dwarfs, planets, or massive compact stellar remnants: neutron stars and black holes.

1 Introduction: History of finding unseen stars in binary systems

The history of finding unseen stars in binary systems dates back to 1783 when regularity and periodicity in variation of the magnitude of β Per, called Algol, was noticed visually and interpreted as the interposition of a large body orbiting around the star by Goodricke ([1]). It should be noted that this finding of an eclipsing binary was even before the apparent double stars and the binary stars orbiting under mutual gravitational attraction were first discriminated by William Herschel ([2]). The first visual binary orbits were calculated in the early 19th century, but very few gravitationally bound binary systems were known to science at that time. The best method to detect such binaries was then astrometry. Using this method, Bessel ([3]) discovered that the proper motion of α CMa, Sirius, in right ascension was not constant and he postulated the presence of an unseen companion disturbing Sirius' apparent position.

Development of spectroscopy and astrophotography brought about a revolution in the field of binary stars at the end of the 19th century. In 1890, Vogel ([4]) noticed that the radial velocity of the star Algol, measured from the Doppler shift of the star's spectral lines, varied in accordance with the eclipses. He thus established the first spectroscopic binary (SB1), wherein one set of spectral lines was observed to shift according to the orbital phase. In the same year, Pickering ([5]) detected two sets of spectral lines (i.e. an SB2 binary) in the absorption spectrum of ζ UMa.

Binary orbital motion causes a periodic variation in the path length travelled by light emitted from a star and arriving at Earth. Hence, if the star is regularly pulsating, the observed times of maxima in

⋆shibahashi@astron.s.u-tokyo.ac.jp
⋆⋆simon.murphy@sydney.edu.au
⋆⋆⋆tim.bedding@sydney.edu.au

luminosity vary over the orbit. It was only about 40 years ago that the light-time effect on the pulse timing was first utilized to find unseen binary companions. This won Hulse and Taylor the Nobel prize for their work on a binary pulsar ([6]), and progress was being made on the application to main-sequence stars around the same time. Based on deviation of the photoelectrically observed ephemeris for the times of luminosity maxima from the prediction, a binary nature was first suggested by Barnes and Moffett ([7]) in 1975 for a high-amplitude δ Sct star, SZ Lyn; the suggestion was confirmed correct by radial velocity measurements in 1988 ([8]).

2 New techniques: The FM method and the PM method

The pulse timing method may work very well in the case of stars pulsating with a single mode, because the intensity maxima from the single mode, particularly in the case of sharp maxima, are easy to track and then any deviations from precise periodicity are easy to detect. However, when the pulsating star is multiperiodic the situation becomes complex. It is more desirable to extract phase information for multiple modes systematically. This problem was first discussed by Woltjer ([9]) and later by Irwin ([10]). However, the required photometric and timing precision was not reachable at that time, hence application of their methods was not practical.

In contrast, recent space-based photometry has made it possible to measure the orbital phase variation of pulsating stars in binary systems with extremely high precision over long time spans. Shibahashi and Kurtz ([11]) resorted to the frequency domain to analyse the photometry data, and showed that the phase variation of each mode caused by the light-time effect manifests itself, in the Fourier transform, as a multiplet with spacing equal to the orbital frequency as far as pulsations are coherent over the orbital period as in the case of δ Sct variables. Their method to obtain an orbital solution, called the Frequency Modulation (FM) method, was later improved ([12]) and the validity of the FM technique was verified by the consistent results obtained from it when compared to a traditional eclipsing binary light-curve analysis ([13]).

Soon thereafter, Murphy et al. ([14]) developed a complementary method to be applied in the time domain, called the Phase Modulation (PM) method, which works by converting the phase shifts into the light arrival-time delay for many oscillation frequencies simultaneously ([15]). If multiple oscillation frequencies show the same periodic time delays, the origin can be attributed to binarity. The PM method was further strengthened by adapting automation with a Markov-chain Monte Carlo (MCMC) algorithm to obtain robust uncertainties in the determined orbital elements ([16]). In some binary systems, two series of time delays are identifiable with the same period but opposite phase. This indicates that both binary components pulsate. In such a case, the mass ratio of these systems can be obtained by the PM method without dependence on the inclination $\sin i$, making them very attractive to study. We refer to these as "PB2" systems by analogy with the SB2 spectroscopic binaries.

3 Application of the PM method to exoplanet hunting

It took 18 years to detect Sirius' white-dwarf companion directly ([17]), and Algol's companion is now known to be a cool subgiant. However, some companions are not directly detectable because they do not emit their own visible light. Planets fall into this category. It was the pulse timing method applied to a millisecond pulsar, PSR1257+12, that led in 1992 to the first success in detecting an exoplanetary system ([18]). The discovery of a giant planet orbiting a hot subdwarf B star, V391 Peg, was also made by the pulse timing method ([19]).

Detection of an exoplanet orbiting around a solar-type star was first made in 1995 from spectroscopic observations of the star's radial velocity ([20]). High-precision photometric measurements also led to the success in detecting partial eclipses due to planetary transits across a sun-like star in 2000 ([21]). The former is called the RV method in the field of exoplanet hunting, while the latter is called the transit method. Ultra-high precision, high-cadence photometric measurements from space missions such as the *Kepler* Space Telescope has rapidly accelerated progress in exoplanet searches.

Most of the thousands of planets (and planet candidates) detected by *Kepler* have been found around cool stars ([22]), while exoplanets orbiting A stars remain difficult to find both by the RV method and the transit method. This is because the RV method is hindered by significantly broadened spectra due to rapid rotation of A stars and a lack of suitably shallow absorption lines, while the transit method is hindered by the luminosity variations caused by stellar pulsations, which amount to several mmag. Fortunately, pulsations that limit RV and transit surveys of A stars can themselves be used as precise clocks for the FM or the PM methods. Both the FM and the PM methods are capable of detecting companions down to brown dwarfs or even planetary masses when applied to the *Kepler* data of δ Sct stars. They also complement the spectroscopic radial velocity measurement with sensitivity at long periods of several hundred days, where radial velocity amplitudes tail off. By applying the PM method, Murphy et al. ([23]) succeeded in detecting a 12 $M_{\rm Jup}$ planet in an 840-day orbit around a main-sequence A star. This is the first case (and only one yet) of an A star known to host a planet within the habitable zone.

4 Future application of the PM and FM methods to search for stellar-mass black holes

The contrast between bright intermediate-mass stars and planets is so great that the planets are essentially invisible. The same is true when the optical counterpart is a neutron star or black hole. We then plan to search for stellar remnants, namely white dwarfs, neutron stars and black holes as binary components of pulsating stars by using the PM or the FM methods. If we consider the case of δ Sct stars as the pulsating stars, they are intermediate-mass stars (1.4 to 2.4 $M_\odot$) on or near the main sequence that lie within the classical instability strip. The lower limit for the mass of the binary companion is obtained by either the PM or the FM method. Thus, any luminous companions that have dynamic masses above around 1.4 $M_\odot$ should pulsate, or should be more massive than the instability strip boundary (i.e., $M > 2.4\,M_\odot$) and dominate the spectrum at optical wavelengths. Otherwise, the companions are non-luminous and are therefore compact objects. Specifically, if the dynamical masses of the companions exceed the Chandrasekhar limit (1.4 $M_\odot$), the companions should be neutron stars or black holes. If the masses of the companions exceed the mass limit for neutron stars ($\sim 3\,M_\odot$), the companions should be black holes.

Only around 20 stellar-mass black holes have been found to date ([24, 25]), and they have all been found through their X-ray emission and high energy physics. However, stellar evolution theory tells us they should be ubiquitous, and hundreds of their progenitors within 1 kpc of the Sun are known. The discovery of black holes in the optical through their gravitational interactions would be a major scientific breakthrough, and is well within the capabilities of the PM and FM methods. Stellar evolution theory also predicts that many main-sequence stars should have neutron stars as companions, to which the PM and FM methods are also expected to be sensitive, and which are even more common. We will conduct a thorough search for such objects.

References

[1] Goodricke, J., Phil. Trans. Roy. Soc. London, **73**, 474 (1783)
[2] Herschel, W., Phil. Trans. Roy. Soc. London, **92**, 477 (1802)

[3] Bessel, W. F., MNRAS, **6**, 136 (1844)
[4] Vogel, H. C., AN, **123**, 289 (1890)
[5] Pickering, E. C., MNRAS, **50**, 296 (1890)
[6] Hulse, R. A., & Taylor, J. H., ApJL, **195**, L51 (1975)
[7] Barnes, T. G., & Moffett, T. J., AJ, **80**, 48 (1975)
[8] Moffett, T. J., Barnes, T. G., Fekel, F. C., Jr., Jefferys, W. H., & Achtermann, J. M., AJ, **95**, 1534 (1988)
[9] Woltjer, J., Jr., BAN, **1**, 93 (1922)
[10] Irwin, J. B., ApJ, **116**, 211 (1952)
[11] Shibahashi, H., & Kurtz, D. W., MNRAS, **422**, 738 (2012)
[12] Shibahashi, H., Kurtz, D. W., & Murphy, S. J., MNRAS, **450**, 3999 (2015)
[13] Kurtz, D. W., Hambleton, K. M., Shibahashi, H., Murphy, S. J., & Prša, A., MNRAS, **446**, 1223 (2015)
[14] Murphy, S. J., Bedding, T. R., Shibahashi, H., Kurtz, D. W., & Kjeldsen, H., MNRAS, **441**, 2515 (2014)
[15] Murphy, S. J., & Shibahashi, H., MNRAS, **450**, 4475 (2015)
[16] Murphy, S. J., Shibahashi, H., & Bedding, T. R., MNRAS, **461**, 4215 (2016)
[17] Bond, G. P., AN, **57**, 131 (1862)
[18] Wolszczan, A., & Frail, D. A., Nature, **355**, 145 (1992)
[19] Silvotti, R., Schuh, S., Janulis, R., et al., Nature, **449**, 189 (2007)
[20] Mayor, M., & Queloz, D., Nature, **378**, 355 (1995)
[21] Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M., ApJL, **529**, L45 (2000)
[22] Coughlin, J. L., Mullarly, F., Thompson, S. E., et al., ApJS, **224**, 12 (2016)
[23] Murphy, S. J., Bedding, T. R., & Shibahashi, H., ApJL, **827**, L17 (2016)
[24] Cowley, A. P., ARA&A, **30**, 287 (1992)
[25] Casares, J., in *Black Holes from Stars to Galaxies – Across the Range of Masses*, Proc. of IAU Symposium 238, ed. V. Karas & G. Matt, p. 3 (2007)