Ellipsoidal Modulations of Black Hole Binaries

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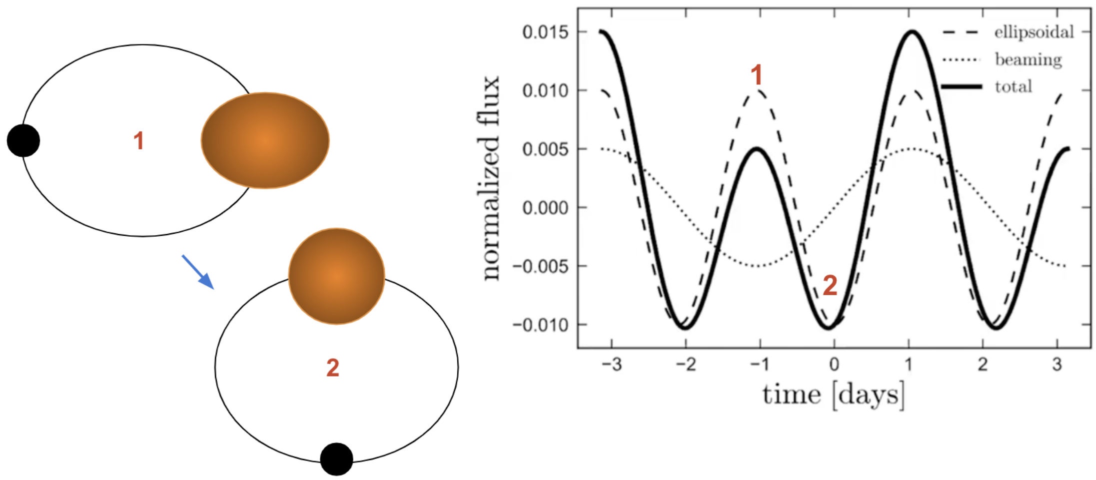

Figure 1: A qualitative picture of ellipsoidal modulation, not to scale. The cartoon on the *left* shows a black hole-luminous companion binary. The tidal forces due to the black halo distort the star and cause the light curve to show an ellipsoidal modulation, as depicted by the dashed line on the *right*. Doppler beaming causes an additional oscillation of the light curve (dotted line). The combination of the beaming and ellipsoidal modulation create a distinct light curve shape (solid line). The light curves are taken from Kareem El-Badry's summer 2020 Princeton colloquium.

When a star is in a binary with a compact object, it can be tidally distorted such that its light curve shows ellipsoidal modulations. These light curve oscillations can be used to search for relatively short period detached black hole binaries using already operational surveys, such as TESS.

Background on Ellipsoidal Modulations

The tidal distortion of a luminous companion by a compact secondary is illustrated in Figure 1. This distortion causes the projected area of the secondary to change with the orbital phase ϕ. To the lowest order, the amplitude of the variations can be written (Masuda & Hotokezaka, 2019)

$$\left|\frac{\Delta L_{\rm ell}}{L}\right| = \alpha_{\rm ell}\frac{M_\bullet \sin i}{M_*}\left(\frac{R_*}{a}\right)^3 \sin i \sim 0.0189\,\alpha\,\sin^2 i\left(\frac{P}{1\,{\rm day}}\right)^{-2} \times \left(\frac{\rho_*}{1\,{\rm g\,cm^{-3}}}\right)^{-1} \times \left(\frac{1}{1+q}\right). \quad (1)$$

Here, $\alpha_{\rm ell} \sim 1$ encompasses effects due to limb- and gravity-darkening (Morris & Naftilan, 1993). R_*, M_*, and $\rho_* = \frac{M_*}{4/3\pi R_*^3}$ are the stellar parameters. $M_\bullet$ is the black hole mass, $q = M_\bullet/M_*$ is the mass ratio, a is the semi-major axis, and i is the inclination. The period of the variations is half the orbital period because the projected area of the star is the same at phases ϕ and $\phi + \pi$.

In practice, a large scale program to identify detached stellar mass black hole binaries by searching for solely ellipsoidal modulation is impossible, given that many other configurations can produce such light curves. Thus, it is optimal to include the effects of doppler beaming, which causes an amplitude variation (Loeb & Gaudi, 2003; Masuda & Hotokezaka, 2019)

$$\left|\frac{\Delta L_{\rm beam}}{L}\right| = \alpha_{\rm beam}\, 4\frac{K_*}{c} \sim 0.0028\,\alpha_{\rm beam}\,\sin i\, q\left(\frac{P}{1\,{\rm day}}\right)^{-1/3} \times \left(\frac{M_\bullet + M_*}{1\,M_\odot}\right)^{-2/3}. \quad (2)$$

Here, K_* is velocity semi-amplitude. Modulation due to beaming has a period twice as long and is typically out of phase with ellipsoidal modulation. The sum of the elliptical modulation and beaming (solid line) produces a distinctive light curve.

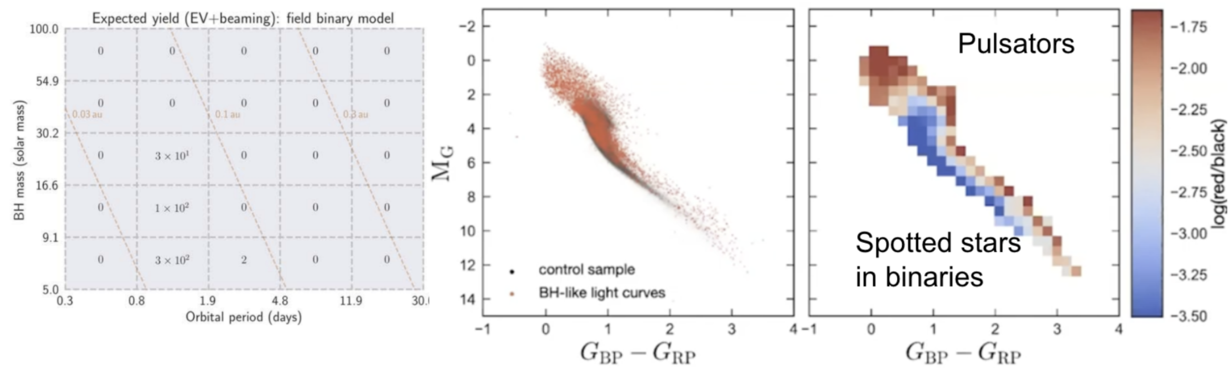

Figure 2: (*left*) Predictions for the number of black hole-luminous companion binaries detectable by TESS. Figure from Masuda & Hotokezaka (2019). (*right*) Color magnitude diagram for all TESS stars and those which show signatures of beaming and ellipsoidal modulation. The *far right* shows the ratio of the density of black hole binary candidates to normal stars. Most of the hot, high mass stars are pulsators, while the cool, low mass stars are spotted stars in binaries. (*right*) panels taken from Kareem El-Badry's summer 2020 Princeton colloquium.

Detecting Stellar Mass Black Hole Binaries with Ellipsoidal Modulation

Light curve oscillations due to ellipsoidal modulations and beaming in black hole-star binaries are already detectable, and have been detected, by surveys including OGLE (e.g. Gomel et al., 2021) and ASAS-SN (e.g. Jayasinghe et al., 2021). Here, we focus on the Transiting Exoplanet Survey Satellite (TESS). TESS is a full sky survey which provides > 27 day long light curves with a 30 minute cadence. It will ultimately observe $> 10^7$ stars with a sub-percent photometric precision (Ricker et al., 2015).

Masuda & Hotokezaka (2019) used models of the expected ellisoidal modulation and beaming signals, combined with the TESS sensitivity, to predict how many such events TESS should detect. They attempted to account for possible confusion with star spots by imposing a threshold on the modulation amplitude. They tested different models of black hole binary formation, and their results for a model where black hole binaries form as field binaries are summarized in Figure 2. They expect $\sim 10 - 100$ binaries to be visible with TESS.

Kareem El-Badry has searched the TESS catalog for these characteristic light curves. He has identified thousands of candidates, although all of those he has followed up so far have proven to be, e.g., pulsating stars. A promising avenue to reduce this large background is to combine multiple methods of searching for dormant black hole binaries. For example, one can require that all candidates are also detected in spectroscopic surveys such as SDSS-V and show radial velocities consistent with a black hole binary interpretation (Kareem El-Badry Princeton colloquium, 2020).

References

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