
133. Ellipsoidal variables and black holes

ELLIPSOIDAL VARIABLES are close binaries with orbit inclinations too small to yield eclipses, but with components nonetheless distorted by their mutual gravitation. Their quasi-sinusoidal light curves are a result of the changing projected areas and surface brightnesses of the distorted stars. Incidentally, other photometric signatures of close non-eclipsing systems include the reflection of each star's light from the other's surface, and the relativistic Doppler beaming of the light due to their orbital velocities (e.g. Faigler & Mazeh, 2011).

The semi-amplitude of the ellipsoidal effect depends on the stellar radii and binary separation, but even for the closest systems, $a \lesssim 15R_*$, it is only of the order of a few per cent (e.g. Morris & Naftilan, 1993).

In an early compilation, Morris (1985) listed some 20 confirmed ellipsoidal variables, and a similar number of suspected systems. Their number has increased substantially since, in particular with the photometric monitoring by the Kepler mission, and with some 15 000 most recently found with TESS (Green et al., 2023).

THE GROWING INTEREST in ellipsoidal variables is partly motivated by efforts to further understand stellar evolution. Binary systems, particularly those with short orbital periods, are the progenitors of cataclysmic variables, supernovae, and gravitational wave-generating neutron star and black hole mergers. The complex evolutionary processes that lead from an initial main-sequence pair to the final merging stages remain poorly understood, and are best-probed by large uniform samples of various small-separation systems.

Ellipsoidal variations have also been observed in star-planet systems, in which tidal distortion of the star by the planet results in a periodic flux modulation (twice per orbit) due to changes of the star's visible surface area as the stellar tide, created by the planet, rotates in and out of view. Such photometric signatures were first seen in the Kepler data of HAT-P-7 b (Borucki et al., 2009), and in a handful of other exoplanet systems since, including CoRoT-3 (Mazeh & Faigler, 2010) and WASP-12 (Cowan et al., 2012).

GAIA IS PROVIDING a new hunting ground for binary systems. For long orbital periods and wide component separations, El-Badry et al. (2021) defined a sample of 1.1 million resolved binary systems with $a \gtrsim 50$ au. At closer separations, Gaia DR3 includes orbital solutions for some 800 000 astrometric, spectroscopic and eclipsing binaries (e.g. Vallenari et al., 2022; Bashi et al., 2022; Halbwachs et al., 2022).

As part of their extensive classification of variable stars identified as part of the Gaia DR3 processing chain, Rimoldini et al. (2022, §4.10) identified 65 300 candidate ellipsoidal variables. With Gaia still being at a relatively early processing and classification stage, they consider that their candidates may still be somewhat 'contaminated', for example by W UMa eclipsing binaries.

ONE OF THE AREAS of scientific exploitation of these ellipsoidal variables that is generating considerable interest today, and based on Gaia data, is their role in the search for 'unseen' compact secondaries, either black holes, neutron stars, or perhaps white dwarfs.

The basic idea was already used by Trimble & Thorne (1969), who suggested that the mass function of the bright binary HR 8427 (V365 Lac) implied that the unseen secondary had a minimum mass of $5.2M_\odot$, and was therefore possibly a black hole. Further studies of the system's ellipsoidal light variations by Morris & Naftilan (1993) ruled out this hypothesis.

More recently, refined models of ellipsoidal light curves have been valuable in isolating possible candidates (Gomel et al., 2021b; Gomel et al., 2021a), which have been applied to similar photometric searches based on OGLE data (Gomel et al., 2021c).

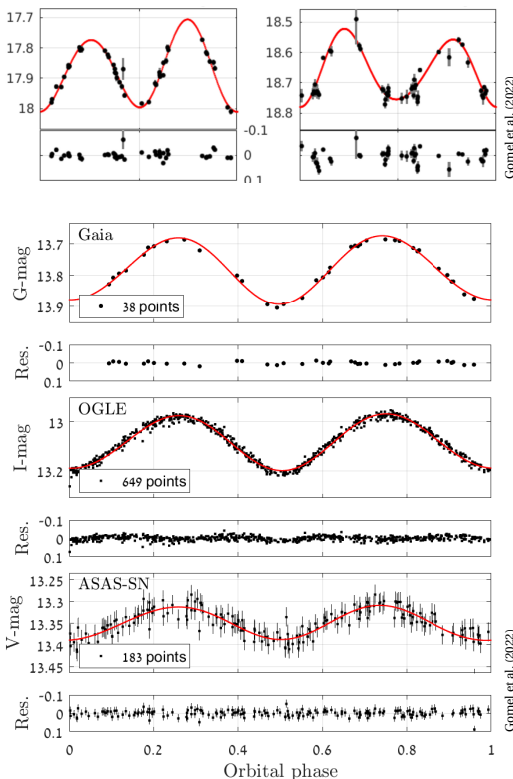
The principles are straightforward: given an observed ellipsoidal amplitude, and the primary star's mass and radius, a minimum mass ratio of the binary can be estimated. A binary with a minimum mass ratio significantly larger than unity might be a candidate for having a dormant compact-object companion. But this approach is hampered by the fact that, in most cases, the primary mass and radius are not well known.

CIRCUMVENTING THE need for knowledge of the primary mass and radius, Gómel et al. (2021b) used, instead, a ‘modified minimum mass ratio’, mMMR, assuming that the primary fills its Roche lobe. The modified minimum mass ratio is always smaller than the minimum mass ratio, which is, in turn, smaller than the actual mass ratio. Therefore, binaries with mMMR > 1 are candidates for having a compact-object secondary.

Applying these principles to Gaia DR3, Gómel et al. (2022) identified 6306 short-period ellipsoidal candidates with relatively large-amplitude modulation in the G-band, mMMR > 0.5, indicating a possible massive, unseen secondary. In case of a main-sequence primary, the more massive secondary is probably a compact object: either a black hole, neutron star, or possibly a white dwarf. They also list 262 systems with mMMR > 1, for which the compact-secondary probability is higher.

Given the two main underlying assumptions, that the light curve is attributable to ellipsoidal variations only, and that the primary is on the main sequence, they emphasise that follow-up radial velocity observations are needed to verify their true nature.

Two examples of the Gaia light curves, used for their object selection, are shown here. The other figure shows the Gaia light curve for one of their three top candidates, Gaia DR3 4042390512917208960, along with light curves from OGLE and ASAS for the same object, all also showing residuals from their three-harmonic fit.

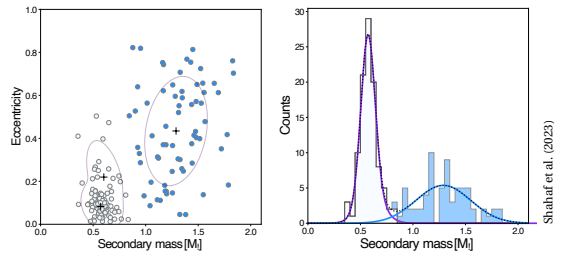


Gómel et al. (2022)

Gómel et al. (2022)

OTHER SIMILAR searches have been undertaken with Gaia DR3. Fu et al. (2022) identified 10 targets having ellipsoidal light curves, variable radial velocity, and high mass function. Two have LAMOST spectroscopy, one of which is a double-lined spectroscopic binary. The observational data of seven are inconsistent, with photometric periods shorter than the minimum orbital periods calculated by the stellar parameters from DR3. After excluding these seven inconsistent targets and another candidate contaminated by a nearby bright star, they consider that the remaining two targets may host compact objects meriting follow-up spectroscopy.

Shahaf et al. (2023) identified 177 systems with probable non-luminous massive companions, including eight candidate black-hole systems with compact-object masses larger than $2.4M_{\odot}$. The eccentricity versus secondary-mass diagram of the other 169 systems suggests a clear separation between the white-dwarf and the neutron-star binaries: most of the former are characterised by small eccentricities $e \sim 0.1$ and masses $M \sim 0.6M_{\odot}$, while the neutron star binaries display typical eccentricities $e \sim 0.4$ and masses $M \sim 1.3M_{\odot}$.



Shahaf et al. (2023)

G AIA IS clearly providing a vast and uniform photometric survey, from which candidate ellipsoidal variables are being identified in unprecedented numbers. Future data releases will provide more densely sampled light curves, and astrometric orbits for many.

But spectroscopy of a number of the candidates identified by Gómel et al. (2022) has resulted in a disappointing yield of massive companions. Nagarajan et al. (2023) selected 14 targets for follow-up spectroscopy, obtaining spectra at 2–10 epochs for each. From the semi-amplitudes of the radial velocity curves, they derived minimum companion masses of $M_{2,\min} \leq 0.5M_{\odot}$ in all cases. Assuming random inclinations, the typical companion mass is $M_2 \sim 0.15M_{\odot}$, making it unlikely that any contain a black hole or neutron star.

Seeking alternative explanations for the ellipsoidal-like variability, they could best reproduce the light curves and radial velocities with models for unequal-mass contact binaries with starspots. Some may also be detached main-sequence binaries, or even single stars with variability due to pulsations or starspots.

The future for finding quiescent black hole companions seems bright... but the hunt continues!