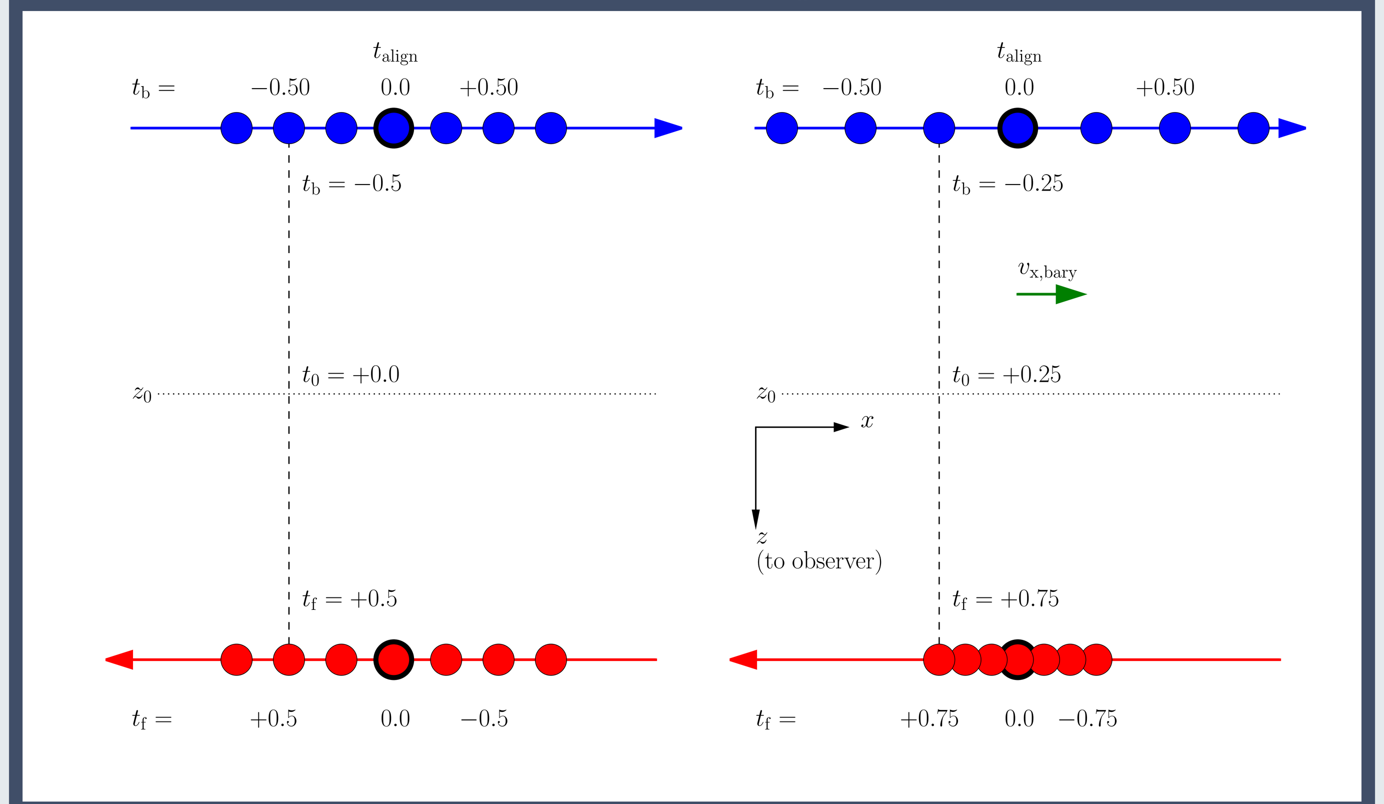
Transverse Motion on Eclipse and Transit Times

Kyle E. Conroy[1,2], Andrej Prša[2], Martin Horvat[2], Keivan Stassun[1]
1. Vanderbilt University 2. Villanova University

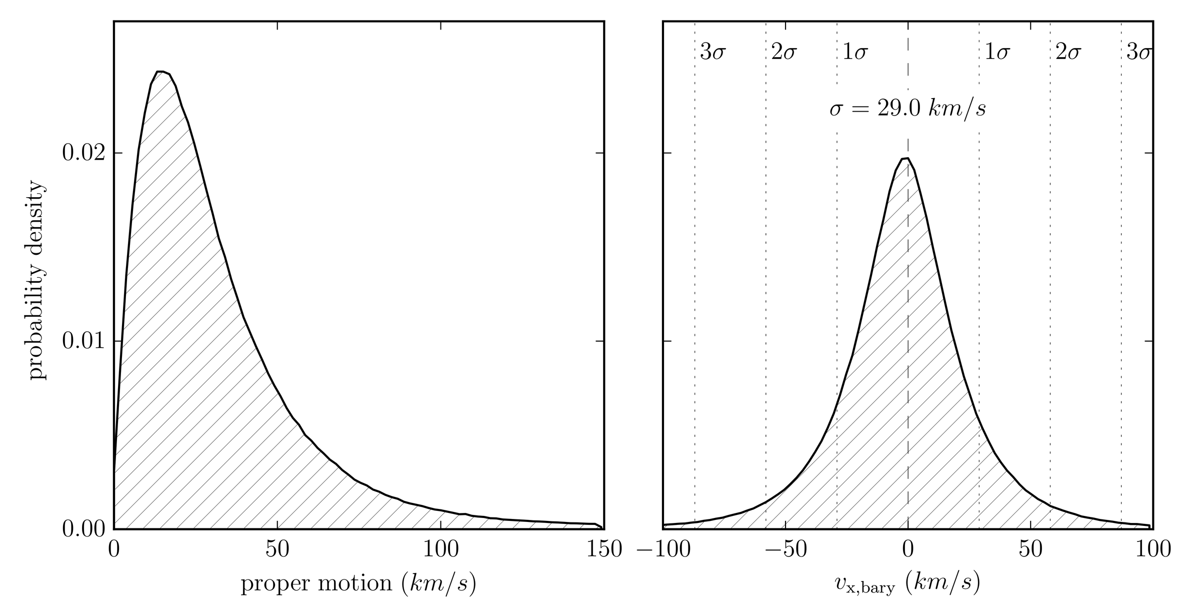
Due to the finite speed of light, any motion of a binary or planetary system towards or away from the observer is known to affect the observed time of an eclipse. Here we present another non-relativistic effect on the timing of an eclipse due to the finite speed of light. It occurs whenever a bulk transverse motion is present, causing an asymmetry in the transverse velocities of the two eclipsing objects. This effect can manifest itself both as a change in the observed phase separation between the primary and secondary eclipse, as well as a time-dependent contribution to eclipse timing variations. We demonstrate this effect's influence on the measurement of eccentricity, rate of precession, and the properties of triple systems.

Theory



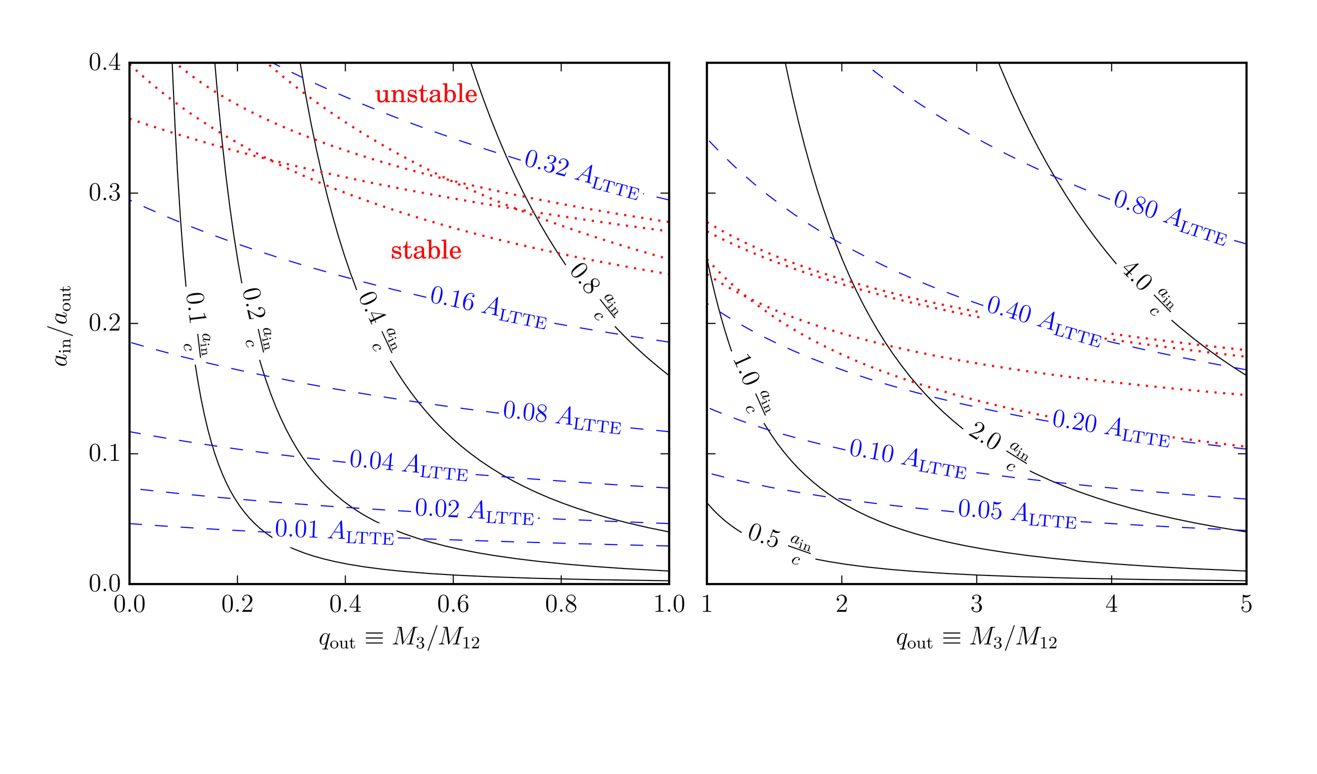
Schematic of Barycentric and Asymmetric Transverse Velocities (BATV) acting on an equal-mass system (left: no barycentric motion, right: positive barycentric motion). The separation between the two components along the line of sight is defined as one light-time unit. The time of eclipse is defined as the time at which a photon leaving the back star (b), traveling along the line of sight (z), and intercepted by the front star (f), passes the plane of the barycenter (z_0). The general expression for the resulting time-shift caused by BATV is as follows:

$$\Delta t_{\rm BATV} = \frac{\Delta z_{\rm bf}}{c}\left(\frac{\xi-1}{\xi+1} - \frac{1}{\xi+1}\frac{v_{\rm x,bary}}{v_{\rm x,f,orb}}\right)$$

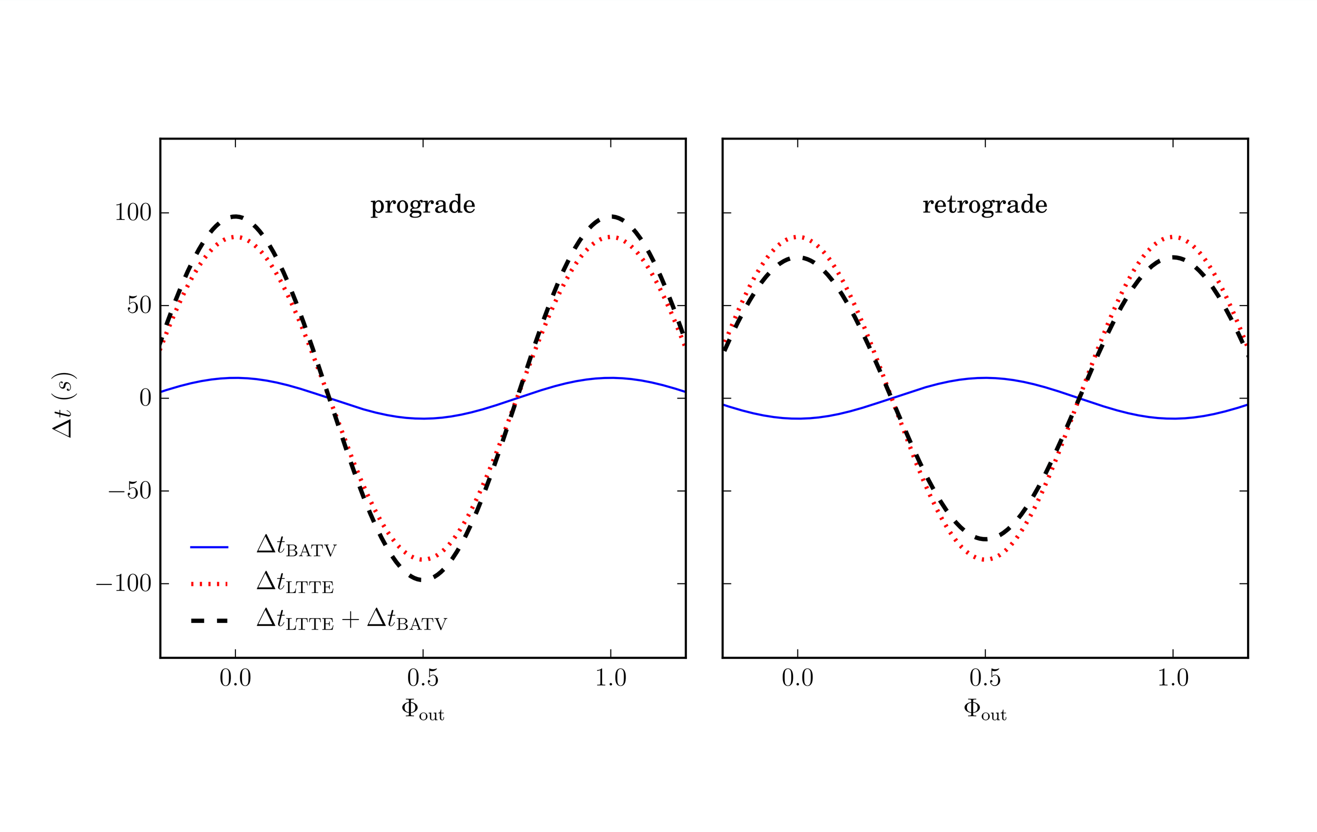


Proper motions in velocity units (left) from GAIA DR1 (Gaia Collaboration et al 2016a,b). Assigning random orientations of a binary system for each of these proper motions results in the predicted distribution of transverse velocities (right).

Triple Systems

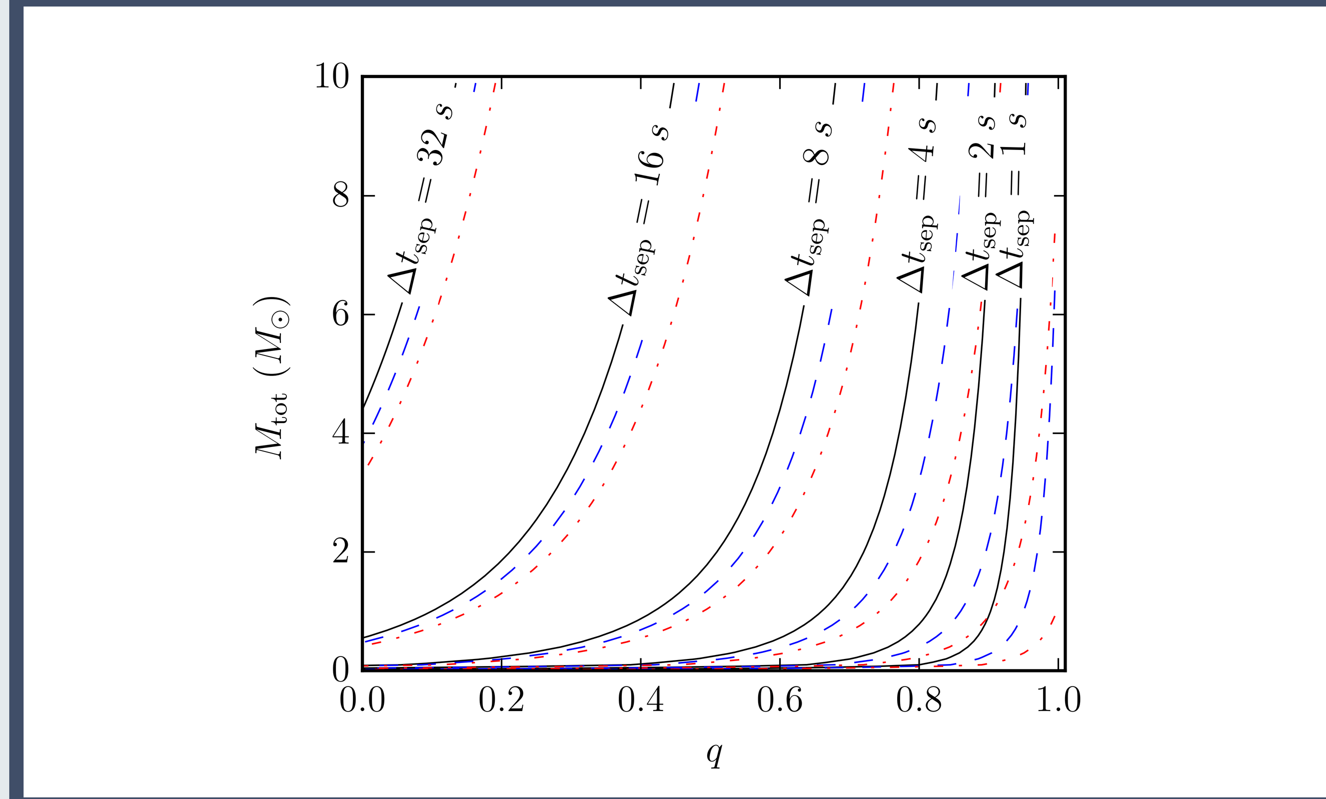


Peak-to-peak BATV amplitude over an entire orbit of the inner-binary within the outer-orbit for the circular and coplanar case, viewed edge-on at i=90°. Solid black contours are in terms of the photon travel time between the two eclipsing components and the dashed blue contours are in terms of the ratio of the amplitude as compared to classical LTTE (light travel time effect; cf. Borkovits et al. 2003). The red dotted lines represent various estimations for the dynamical stability limit, for $q_{\rm in}$=1.



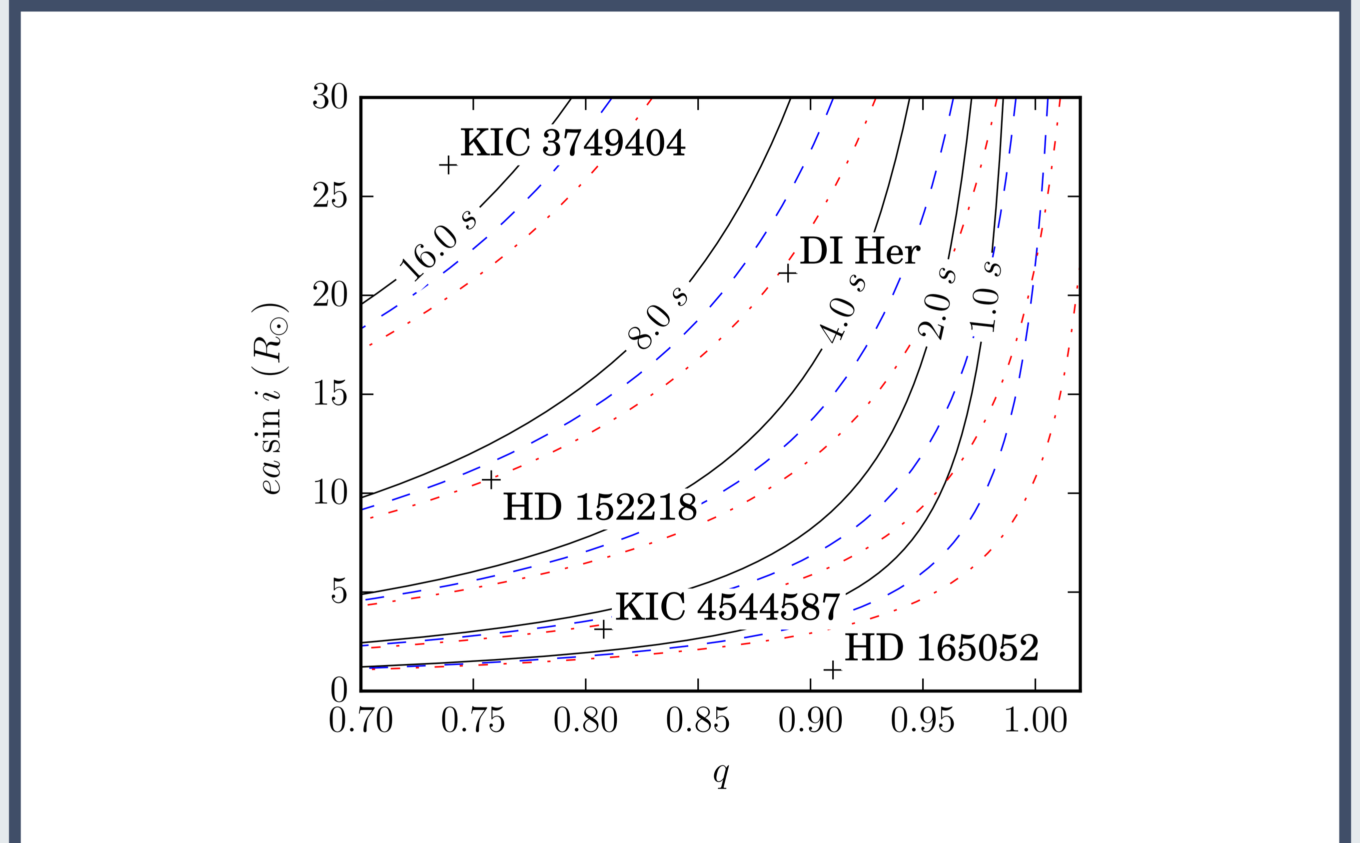
Contribution to ETVs by both classical LTTE (dotted red) and BATV (solid blue) for a circular coplanar hierarchical triple system. Accounting for BATV in the prograde case (left) results in an increase in the magnitude, but a decrease in the retrograde case (right). Failing to account for BATV can therefore affect the resulting estimates on the mass of the third body.

Phase-Separation



Change in eclipse-separation (from the expected 0.5-phase) for a circular edge-on binary with a period of 1.0 d as a function of total mass and mass ratio for $v_{\rm x,bary}/v_{\rm x,f,orb,peri}$ =0% (black), 5% (blue), 10% (red).

Apsidal Motion



Peak-to-peak BATV amplitude over an entire apsidal motion cycle for binary stars (top) and exoplanet systems (bottom) as a function of eccentricity times projected semi-major axis and mass ratio for $v_{\rm x,bary}/v_{\rm x,f,orb,peri}$ =0% (black), 5% (blue), 10% (red).

References

Borkovits, T., Érdi, B., Forgács-Dajka, E., & Kovács, T. 2003, A&A, 398, 1091
Gaia Collaboration et al. 2016a, A&A, 595, A2
Gaia Collaboration et al. 2016b, A&A, 595, A1