How do collisions shape the orbits of irregular satellites?

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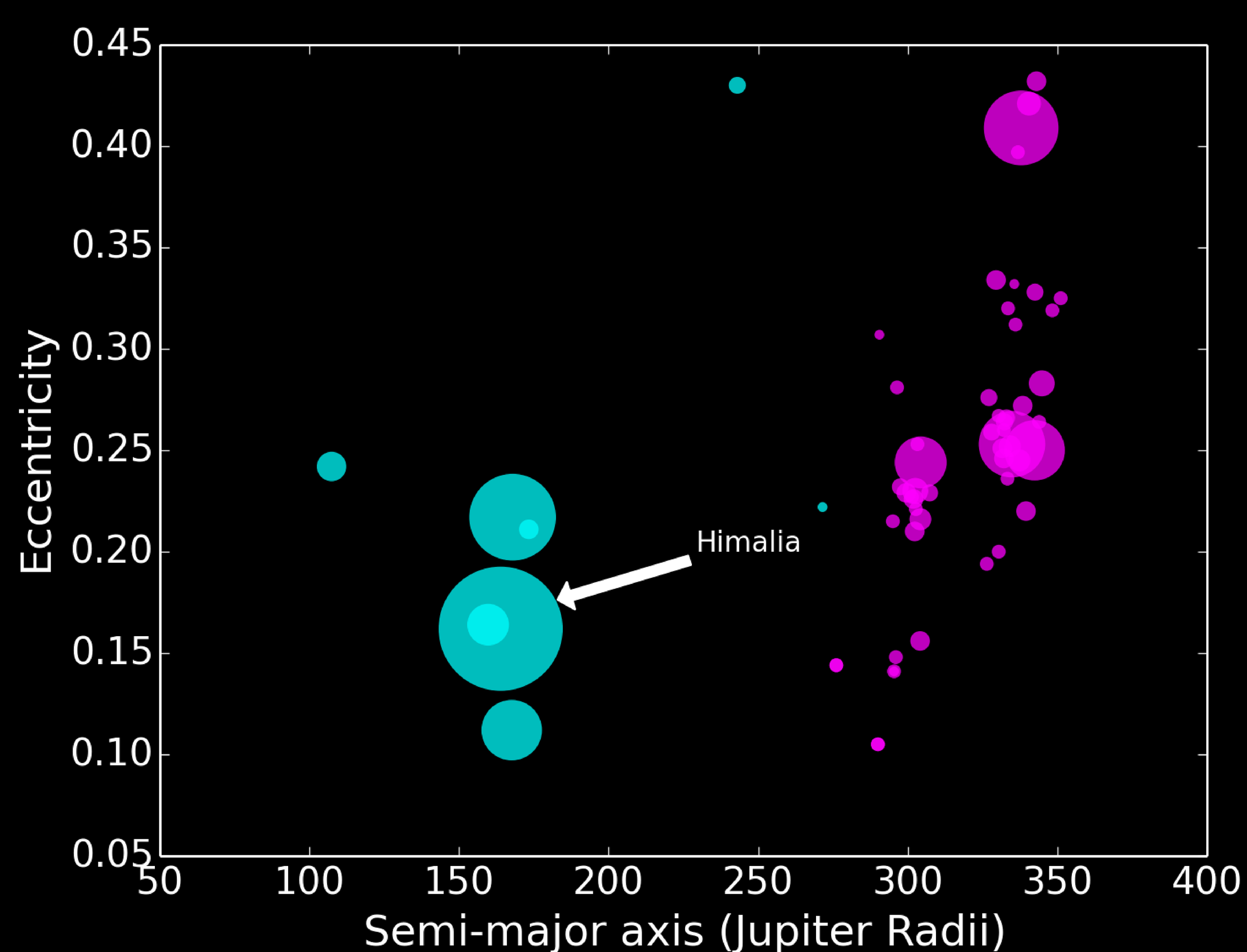
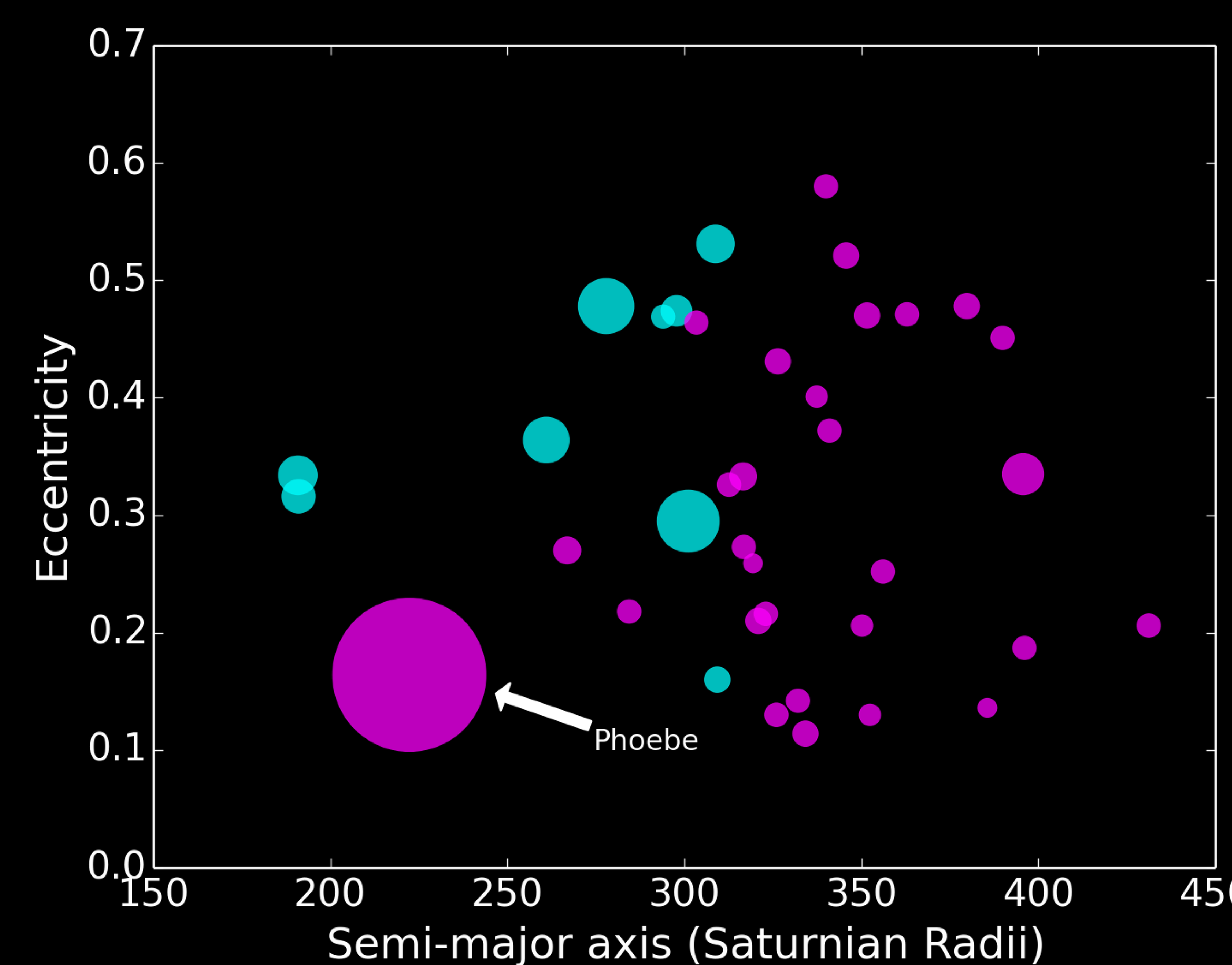
ABSTRACT

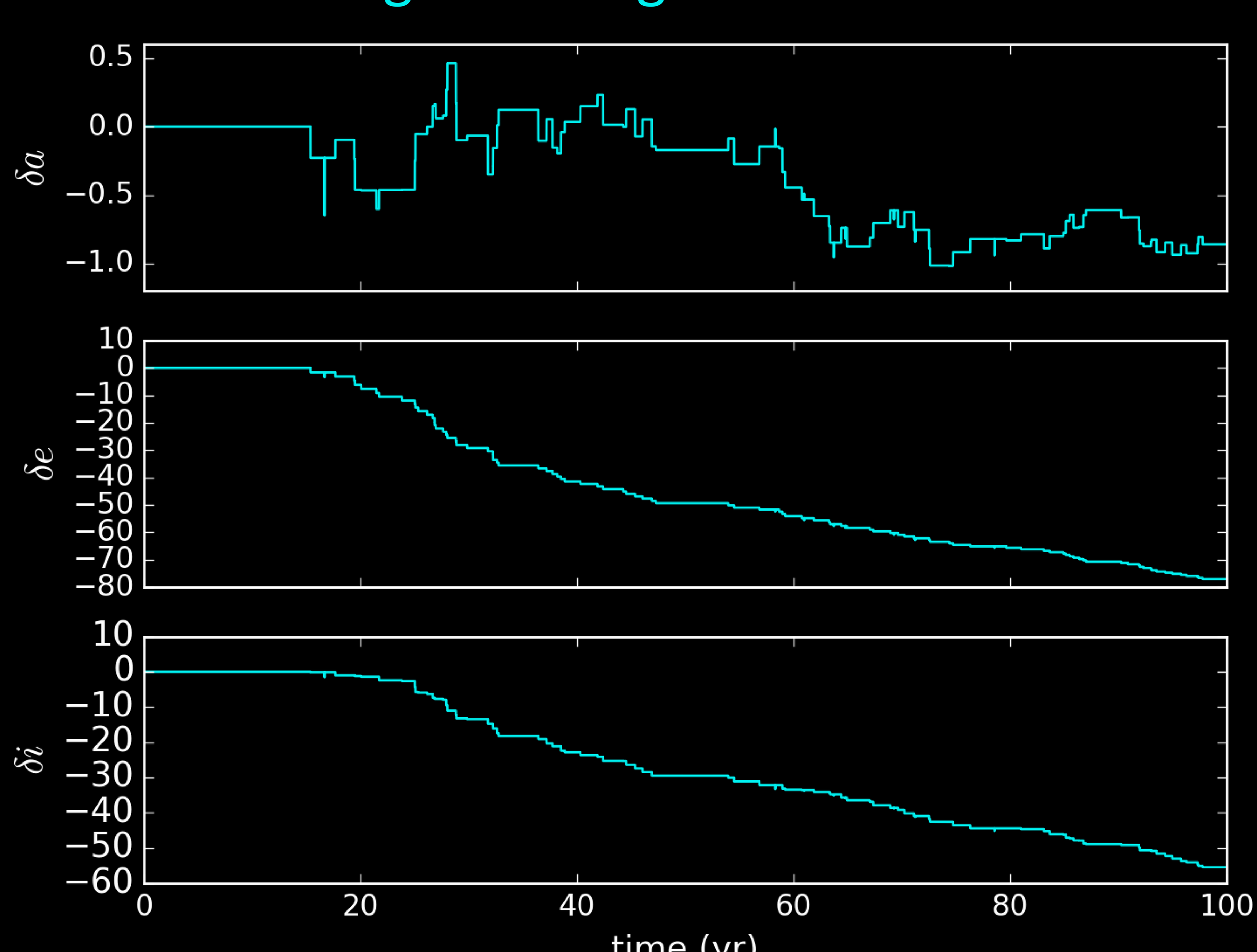
Irregular satellites differ from their regular counterparts by orbiting at great distances, by following highly eccentric and inclined orbits, and, for most of them, by orbiting backwards. They are thought to have formed initially in heliocentric orbits, but were captured by the planets early in Solar System history. These satellite systems were once very collisionally active [1], and these collisions may have shaped their orbital architectures. For instance, the prograde and retrograde satellites around Jupiter revolve in nearly distinct radial regions; although two transitional moons at Jupiter, Carpo and another announced in the summer of 2018, orbit prograde but transit into the retrograde region. While their high inclinations extend their collisional lifetimes, a once well-mixed population would have yielded frequent head-on collisions that lead to annihilation. As orbital velocities around Saturn, on the other hand, are slower, collisions are less frequent and less violent and it is no surprise that its irregular satellite system is more varied. At Jupiter, the largest irregular moon Himalia is prograde while Saturn's largest is Phoebe, which orbits retrograde. These large moons have low inclinations and eccentricities, and are positioned closer to the central planet than the other irregular moons. These similarities may imply a shared genesis [2][3], and we are investigating the significance that collisions have on their formation.



These figures depict the eccentricities of Jupiter's (left) and Saturn's (right) irregular satellites as a function of their semi-major axes. Blue corresponds to prograde satellites, and pink corresponds to retrograde satellites. The sizes of each circle refer to the relative sizes of the satellites.

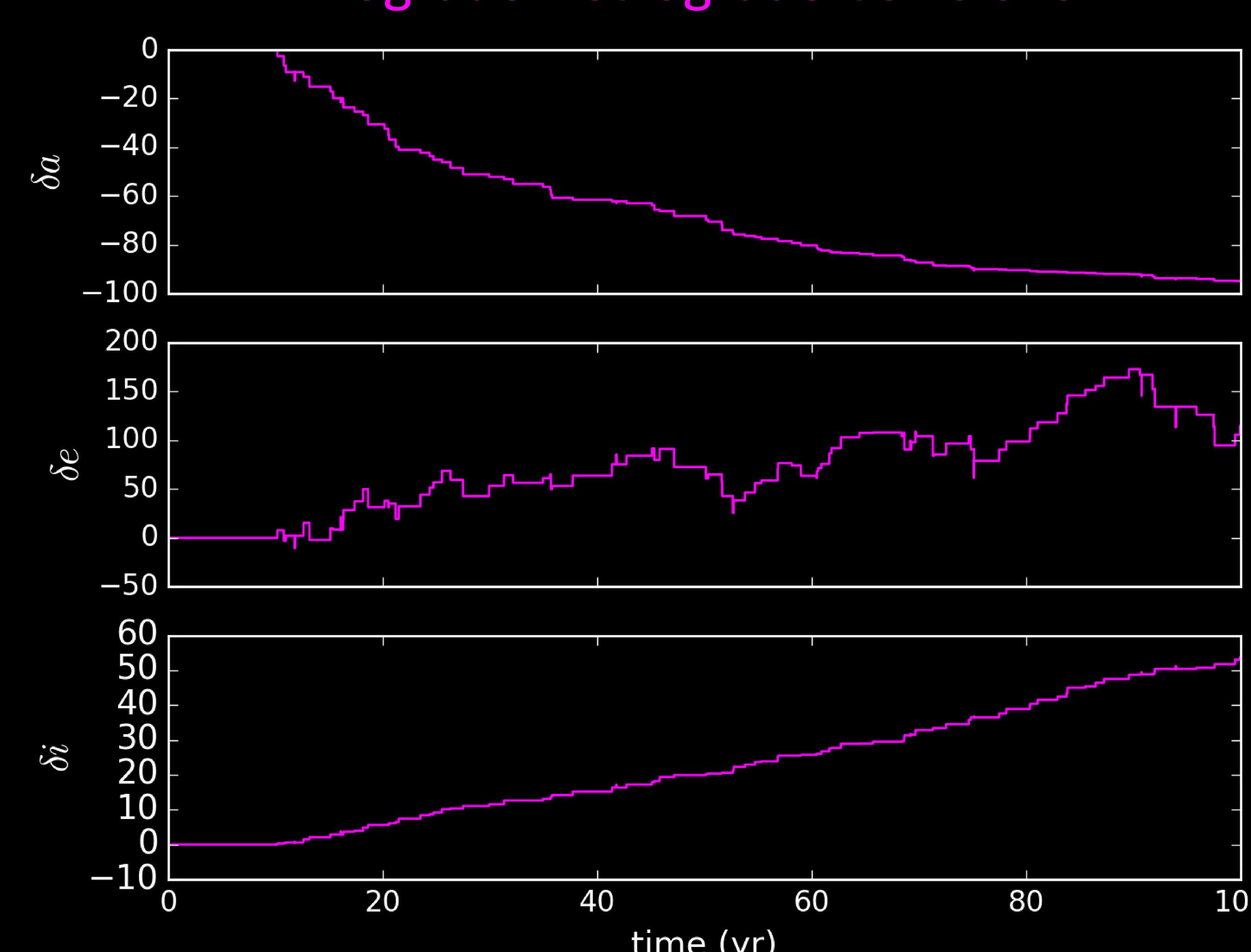


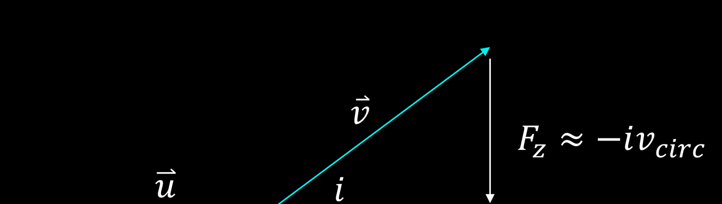
Prograde-Prograde Collisions

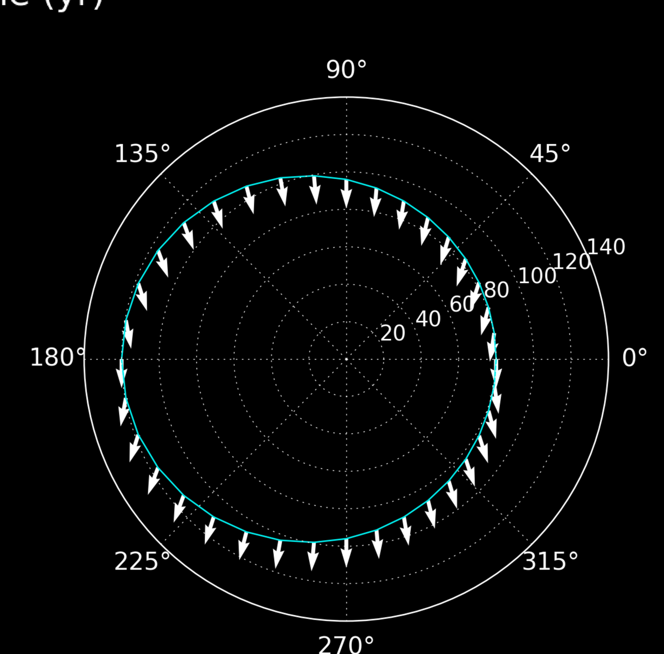


These figures show a satellite orbiting Saturn with an initial semi-major axis of 1.3e7 km, eccentricity of 0.2, and inclination of 5° after being struck by 100 objects that are about 1% of the mass of the satellite over 100 years. The y-axes show the orbital elements' percent relative changes, and the satellite's mass in each case doubles. We calculate the mass of each satellite by using an approximation of the relative velocity of the two bodies upon impact valid for near equal semi-major axes: $v_{rel} \approx ev_{circ}$ [4].

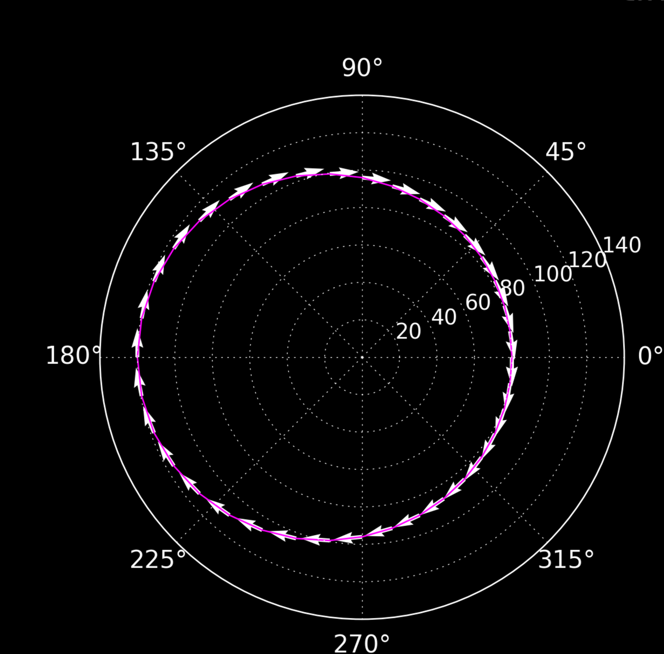
Prograde-Retrograde Collisions

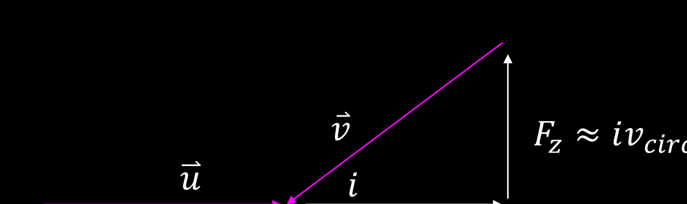






The circular figure on the left shows the direction of the impulses for impactors traveling on circular orbits incident on a satellite with $e = 0.2$ and $i = 0°$ over the entire orbit, where the angles are the true anomaly. The satellite experiences headwind near pericenter and a tailwind near apocenter, so over an entire orbit the satellite's semi-major axis remains relatively unchanged. The vector figure on the left shows the impulse acts to decrease inclinations. The corresponding figures on the right show the direction of the impulses for the opposite case where all the collisions are head-on. Head on collisions cause the semi-major axis to decrease substantially and the inclination to increase.





If Phoebe and Himalia experienced the same number of prograde and retrograde collisions, then their inclinations and eccentricities should remain relatively unchanged while their semi-major axes decrease. If they, instead, experienced fewer retrograde collisions, then we expect their inclinations and eccentricities to decline. Phoebe, at least, may have experienced a similar scenario.

References:
[1] Bottke et al. 2010; [2] Hamilton (2001); [3] Hamilton (2003); [4] Hamilton & Burns (1994); [5] Rauch & Hamilton (2002); [6] Danby (1992)