Formation of the Asynchronous Binary Asteroids

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Abstract

Rotational fission results in the formation of all classes of observed near-Earth asteroid (NEA) binaries including asynchronous binaries, which do not have any synchronicity in their systems. Asynchronous binaries may be formed directly from rotational fission or from the influence of the Yarkovksy-O'Keefe-Radzievskii-Paddack (YORP) effect upon the synchronous population after a planetary flyby or significant expansion of the mutual semi-major axis of the system. These three routes satisfactorily explain the observed characteristics of the asynchronous population including rapidly rotating primaries and secondaries relative to the mutual orbit rate, small and large mass ratios[1], members with large and small eccentricities.

Rotational fission of "rubble pile" asteroids

The NEA population is constantly evolving due to the incredible influence of electromagnetic radiation. The YORP effect, torque from the incident solar irradiation and the thermal radiation of an asymmetric body, can rotationally accelerate individual asteroids until centrifugal accelerations match gravitational accelerations [1], releasing part of the body into orbit and creating a binary asteroid system–i.e. rotational fission. This process has been theoretically predicted and modeled in detail [2, 3, 4], as well as observationally confirmed [5]. In order to rotationally fission, asteroids must have "rubble pile" internal structures–a collection of gravitationally bound boulders with a distribution of size scales and very little tensile strength between them.

Binary asteroid systems comprise a significant fraction ($15 \pm 4\%$) of the NEA population [2, 6]. These systems can be organized into three morphologies based on the spin states of the two members: doubly synchronous–both bodies have the same spin period as the mutual orbit period, singly synchronous–secondary has the same spin period as the mutual orbit period, while the primary has a spin period approaching the rotational speed limit period, and asynchronous–both bodies have spin periods much shorter than the mutual orbit period. Using a simple numerical model, we showed that rotational fission could be responsible for creating stable binaries and asteroid pairs [4], which have been observed within the small Main Belt asteroid population [5].

Simulated large mass ratio systems ($q > 0.2$) did not undergo secondary fission processes and were shown to quickly become doubly synchronous systems [4]. As each member becomes tidally locked and the orbit circularizes, the mutual body tides become weaker and eventually turn off when the system has completely circularized. The system continues to evolve due to the binary YORP (BYORP) effect, which is an averaged, cumulative torque due to asymmetric thermal radiation from a synchronous satellite on the orbit [7]. Since both members are synchronous, both affected by BYORP, and their respective torques add cumulatively. This leads to either very fast contraction (hypothesized source of the contact binary population), relative canceling (hypothesized source of the doubly synchronous binary population), or very fast expansion (one hypothesized source of asteroid pairs) [4].

Simulated low mass ratio systems ($q < 0.2$) often underwent secondary fission processes. Only $\sim 8\%$ of rotational fission events evolved into stable binary systems; the rest becoming asteroid pairs (or multi- member disrupted systems) [4]. Stable binaries spanned a range of semi-major axes (2 - 16 primary radii) and a range of eccentricities (0 - 0.8) with large semi-major axes corresponding to large eccentricities; the median pericenter of 3.3 primary radii being roughly conserved [4].

In Jacobson & Scheeres (2011), tidal evolutionary timescales calculated for the primary and secondary members of stable binaries showed that primaries would not tidally lock within 10 Myr (typically lifetime of an NEA), but most of the secondary members would tidally lock within that timeframe. These tidally locked systems continue to evolve due to tides on the primary and the BYORP effect. Nominally half will have accelerating BYORP torques (hypothetically creating the synchronous binary population after ending up in an equilibrium [8]) and the other half will have decelerating BYORP torques (hypothetically creating asteroid pairs or asynchronous binaries, described below).

Do all binaries synchronize after rotational fission?

No. After rotational fission, stable binary systems with semi-major axes > 8 primary radii remain asynchronous longer than the the typical lifetime of an NEA system, although these systems are evolving towards synchronicity. There are four observed asynchronous binary systems that have orbital periods which place them in this category: (1509) Esclangona, (1717) Arlon, (32039) 2000 JO_{23}, and 1998 ST_{27} [9, 6].

Mutual body tides are not the only torque affecting

[1]Defined as the mass of the smaller (secondary) component divided by the mass of the larger (primary) component of the binary.

the evolution of the spin state of the secondary. The YORP effect is also torquing the secondary, capable of either acceleration or deceleration. If the YORP effect is in the direction for tidal locking, then synchronization proceeds even more quickly. If the YORP effect torque opposes tidal evolution, tidal locking could be prevented entirely. Fang & Margot (2012) determined a semi-major axis, beyond which YORP would dominate the evolution of the secondary's spin state [10].

However, this limit may be too strict. The YORP effect does not need to dominate the spin evolution of the secondary, in order for there to be observable asynchronous binary systems. Systems that are tidally dominated, so they would end up tidally locked given enough time, could have substantial YORP resistance and thus spend significant portions of their NEA lifetimes as asynchronous binary asteroids. This may provide an explanation for asynchronous binary systems such as: (16635) 1993 QO, (35107) 1991 VH, (2577) Litva, and (164121) 2003 YT_1. In fact, YORP dominated secondaries will often accelerate to rotational fission in significantly less than the typical lifetime of an NEA system making them statistically unlikely to be observed. The first evolutionary route from rotational fission to asynchronous binaries isn't much of a route at all, weak tides or stronger tides combined with the YORP effect may prevent stable binaries from evolving out of their initial asynchronous state.

Can synchronization be broken after tidal locking?

Yes. Planetary flybys may impulsively perturb the system or the mutual semi-major axis may expand so far that the gravity gradient and tidal restoring forces are overcome by the YORP torque solely or with the help of excitation of the libration from the conservation of the action. All systems that break synchronicity would naturally return to a tidally locked state without the influence of the YORP effect. As before, these systems last longest as asynchronous binaries when the YORP effect is only slightly inferior or superior to the tidal torque (there is no reason to expect them to ever match exactly).

Fang & Margot (2012) show that flybys may break synchronicity, change the mutual orbit of the system and occur often for NEA binaries, but since they are not themselves capable of rotationally accelerating asynchronous secondaries to their observed spin rates, an accelerating YORP effect is a requirement [11]. Just because a system was initially synchronized does not imply that the YORP torque on the secondary is decelerating, just that at its initial semi-major axis the mutual tidal torque was stronger than the YORP effect. There are a few possibilities that could lead to a different outcome than the initial tidal locking. Since the direction of the YORP torque is dependent only on the shape of the secondary, which presumably would not change significantly for flybys that only alter but do not disrupt the orbit, the strength of the YORP torque would remain similar to before. The tidal torque, which is strongly dependent on the system separation distance, could change strength and become significantly weaker if the system expands. Expansion could be caused by the flyby itself, Fang & Margot (2012) show that a majority of flybys result in this outcome, or the system could have expanded due to tides or the BYORP effect when the secondary was still synchronous. When the secondary is synchronous, the gravity gradient from the permanent shape of the secondary is the strongest restoring torque, preventing the onset of circulation. It is very possible for a system to expand so much so that the YORP torque dominates over the tidal torque, but the gravity gradient prevents the secondary from beginning to circulate. This is a viable mechanism for: (5381) Sekhmet, (16635) 1993 QO,(35107) 1991 VH, (2577) Litva, (162000) 1990 OS, (164121) 2003 YT_1, and 2004 DC.

Flybys are not always necessary. There exists a semi-major axis whereby the YORP effect will overcome the gravity gradient and the system will begin to circulate [12]. The expansion of a system due to the BYORP effect or tides will also excite the libration of the secondary due to the conservation of the action. This excitation grows as the system expands, getting stronger with larger semi-major axes, and will eventually lead to the onset of circulation. After the gravity gradient is beaten, the YORP effect may rotationally excite the secondary to the observed rotation rates. This is a viable mechanism for large semi-major axis systems such as: (1509) Esclangona, (1717) Arlon, and (32039) 2000 JO_{23}.

References

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