A STATISTICAL ANALYSIS OF ASTEROID SPIN AXIS DIRECTIONS: EVIDENCE FOR NON-COLLISIONAL DEPENDENT EFFECTS ON ASTEROID EVOLUTION AND OBSERVATIONAL SELECTION EFFECTS. Luke S. Sollitt[1,2], and Nalin H. Samarasinha[2], 1 The Citadel, Charleston, SC, USA (Luke.Sollitt@citadel.edu); 2 Planetary Science Institute, Tucson, AZ, USA

Introduction: Asteroids can evolve through mechanisms other than collision. In particular, the YORP effect [1] can change an asteroid's spin state through scattering of solar radiation and emission of thermal radiation from the asteroid.

Recent authors (e.g. [2-4]) have been studying this by examining the distribution of asteroid spin axes. If impacts are the dominant driving force behind perturbations to an asteroid's spin axis, then one might expect that distributions in ecliptic longitude and latitude should be relatively isotropic, since impacts are just as likely to occur anywhere on an asteroid, equally likely normal to each body axis [5]. An anisotropy in these distributions might indicate a different evolutionary process(es) at work. For example, prior authors [3,4] found that spin axes of most asteroids tend to have high positive and negative ecliptic latitudes. This may indicate that the YORP effect is causing a net torque along the axis perpendicular to the asteroid orbit plane.

In this work, we use a dataset entirely different from prior authors to look at the distribution of the ecliptic longitudes and latitudes of asteroid spin axes. Furthermore, we transform these longitudes and latitudes into the right-handed coordinate system corresponding to each asteroid's orbital plane, such that the orbital latitude is measured from the orbital plane, and the orbital longitude is measured from the direction of perihelion (as seen from the Sun) in the same sense as the orbital motion. If YORP is responsible for redistributing spin axis latitudes, then it should show more clearly in orbital latitudes than in ecliptic latitudes. Similarly, if there is a preferred ecliptic longitude, then an analogous behavior should also show up in the orbital longitude distribution.

Method: Asteroid spin axis coordinates (ecliptic) were taken from the online Minor Planet Center (MPC) and Poznan Observatory databases as of August 2016 (the latter database is available at http://vesta.astro.amu.edu.pl/Science/Asteroids/). The two datasets were merged and reconciled. Any given asteroid might have a large number of independent spin axis determinations, some of which can be widely different from each other. For this work, the most recent determination was taken to be the 'correct' one, except in circumstances where it had been deemed by the MPC or Poznan Observatory to be not as good (lower quality factor) or where a non-unique solution (discussed below) was more recent than an exact solution. Only those solutions for which a valid sidereal period had been determined were used. The sidereal periods used were those determined by the Minor Planet Center (when available) or the period quoted in the original source for the spin axis determination. In almost all cases, these two periods were identical.

Non-unique solutions: A large number of the spin axis determinations have more than one solution. The most common reason for multiple solutions is non-uniqueness in the ecliptic longitude. This can arise from the use of the magnitude method [6], which gives two solutions. Both solutions usually have roughly the same spin axis latitude, but the sense of the longitude axis will be unclear. That is, the longitude direction plus 180 degrees is just as valid a solution. We did not use spin axes for which there were more than two solutions. This comprised only seven entries in the entire dataset, however.

For two-solution determinations, the angle between the longitudes can be a good stand-in for quality factor as determined by other authors. If the longitudes are roughly parallel or antiparallel, then this likely represents a high-quality determination. If the two directions are normal to each other, then this is a low-quality determination. For this work, we required spin axis determinations to have longitude directions that were different by less than thirty degrees (after accounting for the 180-degree non-uniqueness).

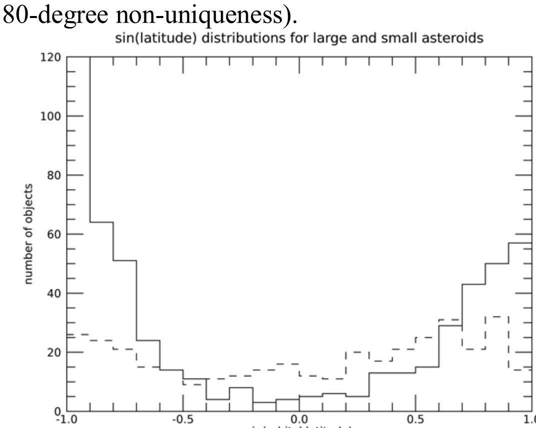

Figure 1. Histograms of orbital latitudes of spin pole axes for asteroids of diameters smaller than (solid line) and larger than (dashed line) 30 km.

The ecliptic longitude used in this analysis was then the average of the two ecliptic longitudes (after correcting for the 180-degree non-uniqueness). In this way, our average was always within 15 degrees of either non-unique longitude, yielding a relatively small uncertainty in the average longitude. Because we were specifically looking at non-unique solutions, we then added or subtracted 180 degrees from all longitudes less than 0 or greater than 180 degrees to obtain a longitude between 0 and 180 degrees. To obtain a unique ecliptic latitude for the non-unique solutions, we average the two non-unique ecliptic latitudes. Orbital longitudes and latitudes are determined using spherical (non-Euclidean) geometry.

Results: *Latitudes:* Figure 1 shows orbital latitudes for asteroids with diameters smaller than (solid line) and larger than (dashed line) 30 km in our dataset. There is a clear bifurcation of latitudes for the smaller asteroids. The distribution for larger asteroids is entirely different: it is essentially flat. The two different behaviors suggest that smaller asteroids must undergo a different post-formation evolution from larger asteroids. As shown in prior findings (e.g. [7]), the spin axes are evolving to higher latitudes as a result of the YORP effect. Similar features are seen for both asteroid populations in histograms of the ecliptic latitudes.

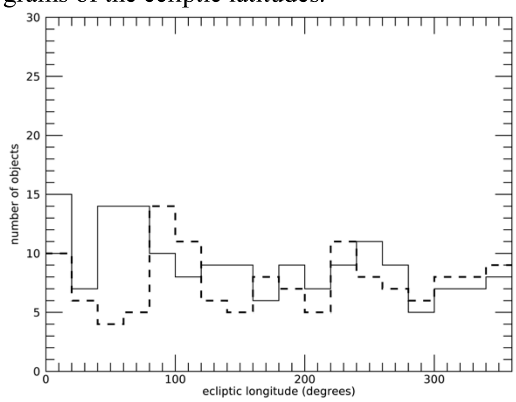

Figure 2. Ecliptic longitudes for small and large asteroids with unique spin axis determinations.

Longitudes: In discussing longitudes, it is useful to break up the discussion into unique and non-unique spin axis determinations. Generally speaking, unique solutions will be better-understood than the non-unique solutions. Figure 2 shows ecliptic longitudes for small (solid line) and large (dashed line) asteroids for which unique spin axis determinations have been made. These distributions are essentially flat, giving rise to no preferred direction in ecliptic coordinates when the spin axis is better-understood.

Figure 3 shows the same plot, but now for ecliptic longitudes for asteroids that have non-unique spin axis determinations. Here, the x-axis only goes from zero to 180 degrees because of the non-uniqueness of the longitude determination: only the direction of the longitude is known. A clear anisotropy centered at approximately 70 degrees ecliptic longitude can be seen for both large and small asteroids. No anisotropy exists for orbital longitudes of unique solutions, nor is there evidence for it in the non-unique solutions.

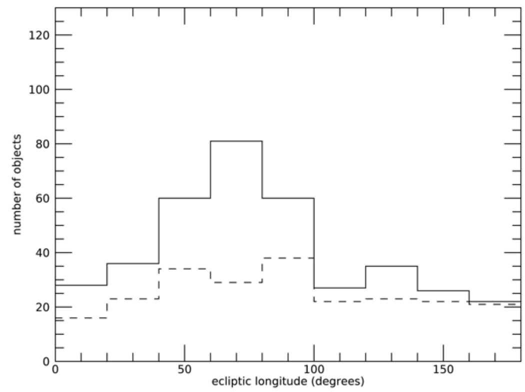

Figure 3. Ecliptic longitudes for small and large asteroids with non-unique spin axis determinations.

Discussion: The completely different behavior in ecliptic longitudes between asteroids of different kinds of spin axis determination, rather than physical size, suggests that this might be an observational, rather than a physical effect. This may be due to two different phenomena. First: the galactic center inhabits a region in space near the ecliptic between about 258 and 288 degrees (ecliptic coordinates). In Figures 2 and 3, this corresponds to a region of the plot between about 78 and 108 degrees, roughly overlapping a substantial fraction of the high-density region in Figure 3. Second: this region of the ecliptic is the one furthest south of the celestial equator. Telescopes in the Northern Hemisphere, which are likely to generate most of the light curves that go into these spin axis determinations, experience the highest atmospheric extinction when observing this area.

The apparent longitudinal anisotropy might arise because of the importance of high-amplitude light curves in the spin axis determination. If the spin axis longitude direction is normal to the direction of the galactic center, then one might lose the high-amplitude light curves, and therefore be less likely to obtain an axis determination for smaller, dimmer asteroids. If the spin axis longitude is closer to the direction of the galactic center, then it is the low-amplitude light curves that might be lost. So, for equally bright asteroids, this observational bias means deriving spin axes near the galactic center is easier.

References: [1] Rubincam, D.P. (2000). *Icarus 148*, 2-11. [2] Cibulkova, H., et al. (2016) *Astron. Astrophys. 596*, id. A57. [3] Bowell, E., et al. (2014) *Meteor. Planet Sci. 49*, 95-102. [4] Kryszczynka, A., et al. (2007) *Icarus 192*, 223-237. [5] Davis, D.R., et al. (1989) In *Asteroids II (R.P. Binzel et al., eds.)*, 805-826, Univ. Arizona Press, Tucson. [6] Magnusson, P. (1986), *Icarus 68*, 1-39. [7] Vokrouhlicky, D., et al. (2003) *Nature 425*, 147-151