Analysis of Asteroid Physical and Osculating Orbital Parameters to Constrain Existing Data Quality and Evolutionary Processes of the Solar System

Jackson Copeland

University of Arkansas Department of Geosciences, GEOS 3873

**Introduction**

Asteroids are minor bodies of the Solar System which orbit the Sun and are too small to be considered planets which are therefore designated the “minor planets.” Sizes range from small particles to the 945 kilometer diameter of Ceres. They are broadly divided into three categories based on composition: C-type, S-type, and M-type for carbonaceous, silicaceous, and metallic, respectively. Believed to be the remnants of collided planetesimals, asteroids are the building-blocks of all planets in the Solar System; their impacts with the rocky planets are highly energetic events which have guided the course of each’s evolution. Life on Earth, for example, is constantly threatened by major asteroid impacts, which have been the causes of major mass extinctions. Although the threat of such large-scale impacts is greatly reduced now compared with the Solar System in its infancy, asteroids also represent a major resource to humanity, both scientific and economic. Not only do they provide a window into the processes that dominated the evolution of the Solar System (and likely other solar systems), but metallic asteroids have immense resource value due to the highly concentrated valuable metals contained within them, as well as the large number and size of such bodies.

There are six Keplerian orbital elements which can describe the orbit of a celestial body. These are: Semimajor axis () - half of the longest diameter of the orbital ellipse, eccentricity () - a unitless measure of the elongation of the orbit, inclination () - the angle between the orbital plane and some plane of reference, longitude of the ascending node () - the angle from a reference direction to the intersection of the orbital plane with the reference plane where the body is “ascending”, or moving upward through the reference plane, argument of periapsis () - or the angle between and the periapsis (shortest distance from the object around which the given body is orbiting), and true anomaly - the position of the body at a certain time or epoch. The parameters of importance for the present study were semimajor axis, eccentricity, and inclination, as well as the derived orbital characteristics of apoapsis (farthest distance from the object around which the body is orbiting) and periapsis.

There are also several physical parameters which were beneficial to consider and utilize. These include: Absolute magnitude - how bright the asteroid would appear if it was one astronomical unit (au) from both the Earth and the Sun at a phase angle of zero, albedo - the reflectivity of the asteroid, diameter, rotational period, and whether or not the asteroid has a natural satellite.

**Abstract**

The present study sought to demonstrate that an analysis of the osculating orbital elements (orbital elements which describe only the current orbits of a celestial body and not the average orbit over longer timescales, in the presence of perturbations) and certain physical parameters of asteroids can reveal features of both the present and past Solar System. In addition, the quality of existing asteroid data was evaluated and accounted for where necessary.

Examining the relationship between asteroid diameter and magnitude, albedo, rotational period, semimajor axis, eccentricity, and presence of a satellite was of principal importance; relationships between albedo and magnitude as well as magnitude and semimajor axis were also examined to better constrain the extent to which the existing data is biased, and histograms of each were constructed for analysis.

**Methodology**

First, it was necessary to analyze the distribution of asteroids with respect to their distance from the Sun. Semimajor axis is the appropriate Keplerian element to use in this situation because it approximates the average distance from the sun for asteroids of roughly spherical orbits. Thus, a histogram of the number of asteroids as a function of semimajor axis was constructed (Figure 1), as well as a plot of orbital inclination with respect to semimajor axis (Figure 2). Subsequent plots of orbital eccentricity with respect to semimajor axis were constructed, and the relationships therein were explored further by differentially coloring asteroids whose periapsis and apoapsis matched certain requirements (Figure 3). Next, the relationship between magnitude and diameter was explored by and plotted (Figure 4) and a very strong nonlinear correlation between the two variables was found (Spearman’s R = 0.75, p < 0.001). A best-fit equation provided by NASA (Eq. 1) was found to fit the data well and was subsequently used to generate diameter data for all asteroids with magnitude values because comparatively few asteroids within the dataset had associated diameter measurements while most had magnitude data. The Monte Carlo method was additionally used on available albedo data to generate random variability for these calculated values (Figure 5). Subsequent plots of diameter and semimajor axis were created for asteroids with and without satellites and running average trendlines were overlain (Figure 6). A plot of albedo vs. semi major axis was also made (Figure 8).

**Results**

Figure 1 shows the histogram of semimajor axis data for every asteroid with (all other values are omitted for clarity due to their comparative sparsity.) The region of 1.75 au < shows the highest density of asteroids by far. The notable gaps in the distribution at 2.06, 2.50, 2.82, 2.96, and 3.28 au are locations at which objects in roughly circular orbits with these semimajor axis values experience resonance effects with Jupiter, called Kirkwood Gaps. Such gaps form because asteroids at these radii experience a periodic “tug” from Jupiter. When this repeatedly occurs in the same locations in the orbit, the asteroid’s orbital trajectory can be significantly altered, and it is pushed or pulled into alternative orbits. The distances at which these effects occur can be calculated using Kepler’s third law:

**Eq. 1**

Kepler’s Third Law simply states that the cube of the semimajor axis is proportional to the square of the orbital period. Thus, for two bodies orbiting the same significantly more massive object, the ratio of the cubes of the two semimajor axes is equal to the ratio of the squares of the two periods. Therefore, the semimajor axis of an asteroid can be calculated for any ratio of orbital periods between it and Jupiter based on Jupiter’s semimajor axis of 5.2 au. Vertical lines in Figure 1 are labelled with the ratio of Jupiter’s period to the period of asteroids at that location.

Chart, histogram

Description automatically generated**Figures**

Figure 1.) A histogram showing the distribution of asteroids with respect to semimajor axis for . The Asteroid Belt (1.54 < ) is shown clearly by the increased proportion of asteroids from roughly 1.75 *au* to . Gaps in the distribution in this region correspond to Kirkwood gaps, which are products of orbital resonances with Jupiter. Vertical lines are semimajor axes at which such resonances occur, and the ratio of orbital periods is given.

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Figure 2) Plot of orbital inclination vs. semimajor axis showing a representation of the distribution of asteroids spatially as well as the presence of asteroid families (Hirayama families).