Mining the SDSS-MOC database for main-belt asteroid solar phase behavior.

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Abstract

The 4th Release of the Sloan Digital Sky Survey Moving Object Catalog (SDSS-MOC) contains 471569 moving object detections from 519 observing runs obtained up to March 2007. Of these, 220101 observations were linked with 104449 known small bodies, with 2150 asteroids sampled at least 10 times. It is our goal to mine this database in order to extract solar phase curve information for a large number of main-belt asteroids of different dynamical and taxonomic classes. We found that a simple linear phase curve fit allowed us to reject data contaminated by intrinsic rotational lightcurves and other effects. As expected, a running mean of solar phase coefficient is strongly correlated with orbital elements, with the inner main-belt dominated by bright S-type asteroids and transitioning to darker C and D-type asteroids with steeper solar phase slopes. We shall fit the empirical H-G model to our 2150 multi-sampled asteroids and correlate these parameters derived from the SDSS colors and position within the asteroid belt.

Introduction

Through collisions with Earth over millions of years, asteroids have influenced our past. Asteroids have been connected as possible candidates to carrying organic components that might answer questions to the origins of life. Through observations we have acquired data to study and analyze numerous asteroids for various factors. By understanding the surface composition, we could use this information for potentially hazardous Near-Earth asteroids whose size and composition determine their level of danger for our planet. Analyzing the density and internal structure of an asteroid can help us determine several things about the impact.

In studying asteroids, we want to develop a better understanding of how the values of solar phase behavior (H,G [which will be defined later]) can be correlated with various parameters of asteroids, such as taxonomy, orbital elements, and position. With this knowledge, we will be able to create a better model of the structure of the asteroids in the main-belt. These data analysis techniques aid in modeling the configuration of the main-belt and in the selection of observational targets due to their intriguing elements.

The term, Near-Earth Object (NEO), is a solar system object whose orbit brings it into close proximity with the Earth. All NEO's have a perihelion distance < 1.3 AU. The term, Potentially Hazardous Asteroid (PHA), is currently defined based on parameters that measure the asteroid's potential to make threatening close approaches to the Earth. Specifically, all asteroids with an Earth Minimum Orbit Intersection Distance (MOID) of 0.05 AU or less and an absolute magnitude (H) of 22.0 or less are considered PHAs.

The phase angle is the angle between the light incident onto an observed object and the light reflected from the object. The moon's phases show the differences in phase angle as the moon moves around the Earth. In images of the phases of Venus, the size of Venus appears to change as its distance to the Earth changes.

Several key terms describe the position of the asteroid as well as its magnitude. Heliocentric refers to the distance measured between the object and the sun. Geocentric refers to the distance measured between the object and the Earth. These two distances allow the observer to calculate the value for H and G. H is known as the absolute magnitude defined as the apparent magnitude that the object would have if it were one AU from both the Sun and the observer and at a phase angle of zero degrees. This process takes out the geometric effects in the magnitude. H will be the y-intercept on all phase curve plots. G is a slope parameter that describes the phase behavior approximately as a straight line. (Binzel et al. 1989)

Project Goal:

The primary goal of this project is to extract solar phase curve information for a large number of main-belt asteroids of different dynamical and taxonomic classes. With this information, we shall fit the empirical H-G model to our 2150 multi-sampled asteroids and correlate these parameters derived from the SDSS colors and position within the asteroid belt.

Methods Used

SDSS is a major multi-filter imaging and spectroscopic redshift survey using a dedicated 2.5-m wide-angle optical telescope at Apache Point Observatory in New Mexico. The purpose of this catalog is to promptly distribute data for moving objects detected by the SDSS. The 4th release of SDSS-MOC is a cumulative release that includes objects from the first three releases.

First, the heliocentric, geocentric, and phase angles at the time of observation were extracted from this database. Then, the orbital elements were extracted. These elements extracted from the SDSS refer to the six Keplerian elements that are the result of Kepler's laws of planetary motion. The main elements that we evaluated were a,e, and i.

The semi-major axis represents values of *a*. The eccentricity of an elliptical orbit is represented by the value of *e*. The amount by which the orbit deviates from circularity: $e = c/a$, where *c* is the distance from the center to a focus and *a* is the semi-major axis. The inclination of an orbit is represented by the value of *i*. The angle between an asteroid's orbit and the plane of the ecliptic (or between a satellite's orbit and the planet's equatorial plane). (Binzel et al. 1989)

The three additional Keplerian elements that should also be noted are the longitude of the ascending node, the argument of periapsis, and the mean anomaly at epoch. The longitude of the ascending node measure the angle between the ascending node and vernal equinox, measured in the plane of the ecliptic. The argument of periapsis refers to the point of closest approach and it defines the orientation of the ellipse. The mean anomaly at epoch is a mathematical representation of the location of a body in its orbital path. It is the product of mean motion and time. Mean motion is defined as the average daily motion for an orbiting body. (Binzel et al. 1989)

Next, we extracted the values for the u'g'r'i'z' filters and their error margins from the SDSS. The two equations and values for Johnson V band magnitude and B band magnitude were also extracted. The u'g'r'i'z' Standard Star System used by SDSS refers to the different type of filters used: ultraviolet, visible, and near-infrared. (Smith, J.A. Et al. 2002)

The variation in brightness of an asteroid can be separated into three components: (1) that due to changing distances from the Earth and Sun; (2) that due to rotation, causing a periodic variation of the area and/or average albedo of the visible surface; and (3) that due to the changing solar phase angle, or angle between the lines of illumination and viewing. (Harris, A.W. & Lupishko, D.F. et al. 1989)

The H, G Magnitude Equation is determined by the alpha phase values that are calculated by solving for Phi. The two constants of A and B were determined through fits with empirical data of asteroids. (Bowell et al. 1989) E. Bowell provides this description of the magnitude system for asteroids. Through implementation of the *H, G* magnitude system that was adopted by IAU Commission 20 in 1985 (Marsden 1986a) [Ast2,549], this project calculated the H and G values for the extracted database of asteroids. The mean V-band magnitude of an asteroid (that is, in the absence of rotational or aspect variations) can be calculated from the formula

$$H(\alpha)=H - 2.5 \log[(1 - G)\phi_1(\alpha) + G\,\phi_2(\alpha)]$$

where $H(\alpha)$ is the V-band magnitude, at solar phase angle α, reduced to unit heliocentric and geocentric distances; H is the *absolute magnitude*: that is, the reduced magnitude explicitly at mean brightness and at α=0 degrees. *G* is termed the slope parameter; indicative of the gradient of the phase curve, it has been scaled in such a way that G ~= 0 for steep phase curves (low-albedo bodies, generally) and G ~= 1 for shallow phase curves (high-albedo bodies), although $G < 0$ and $G > 1$ are not formally excluded. (Bowell et al. 1989)

Four programs were written to extract solar phase curve information, catalog the corresponding data inputs, and organize a comprehensive list for additional analysis.

SORTEDSDSS uses a reduced list of the 2,150 unique objects that had 10+ observations to input asteroid designations into the ASTEROID Program.

ASTEROID reads in and sorts the main SDSS file into IDL vectors of asteroids. Then it searches the organized IDL vectors to match each instance of the input name. Once the input name is matched, it will plot the phase angle and V reduced vectors. A best-fit line will be created. Then the program will exclude those points with error margins that are larger than three sigma values from the best-fit line. Once this task is completed, it will input the phase angles into the program HGPLOT to determine the best H and G value for the asteroid.

HGPLOT uses the H,G Magnitude Equation that has fit the empirical data for other asteroids. It goes through several thousand iterations to calculate the linear least squares from the reduced observed magnitudes.

READER compiles all of the individual data values from the original SDSS file to generate a table that will create a plot of solar phase as a function of semi-major axis.

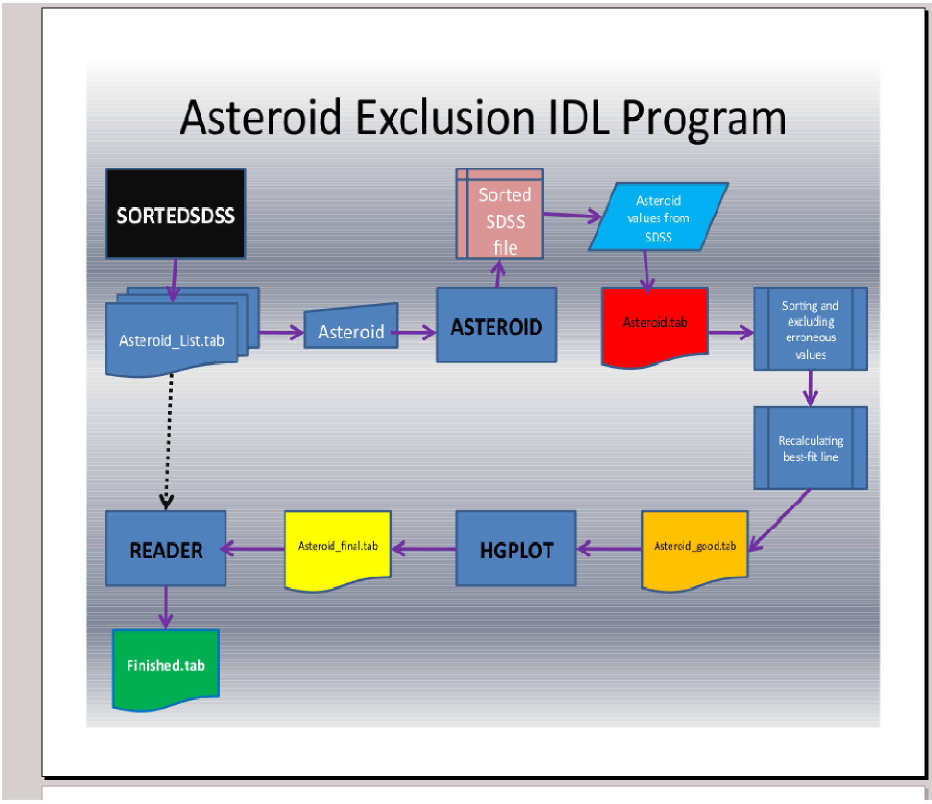


Figure 1

The next two figures will provide an example for a low-albedo asteroid after running the values through SORTEDSDSS. (2002 CT174)

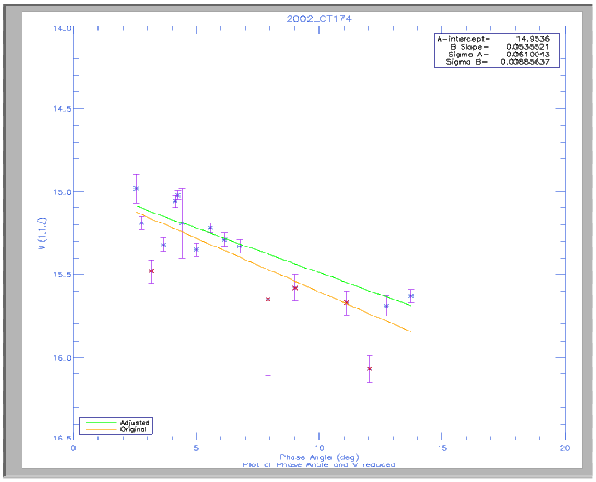


Figure 2

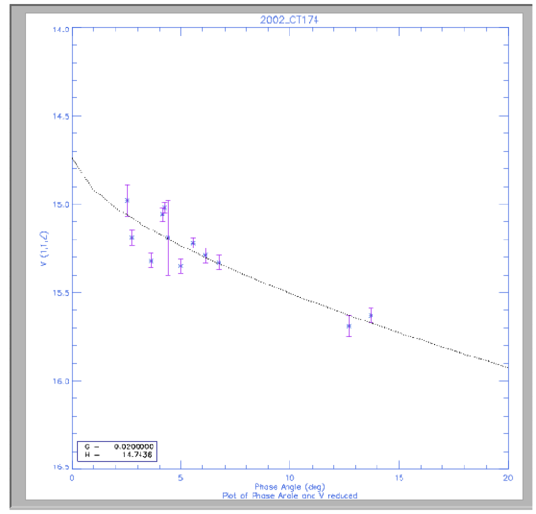
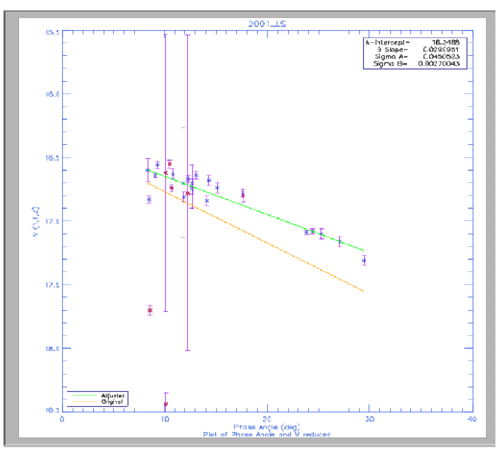


Figure 3

The following figures will provide an example of a high-albedo asteroid. (2001 LS)



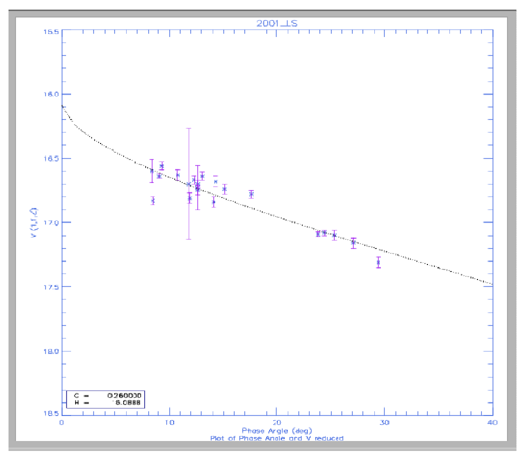


Figure 4

Figure 5

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<u>Taxonomy Types</u>

This project is interested in the two main taxonomy types (C-type and S-type asteroids) that will connect the solar phase behavior to the taxonomic types. The other defined asteroid taxonomic classes correspond to a minor amount of asteroids on the plots. The SMASS classification system provides the criteria for each taxonomic type. (Bus & Binzel et al. 2002) This system utilizes similar definitions to the Tholen classification system that was widely used.

S-type – a very common asteroid class in the inner main belt with moderate albedos and reddish spectra. It is of a siliceous or stony composition. Approximately 17% of known asteroids.

C-type – a very common asteroid type in the outer part of the main belt. They typically have a carbonaceous composition. Approximately 75% of known asteroids.

V-type – a rare asteroid classification exemplified by 4 Vesta. Spectra are very red shortward of 0.5 ṳm,moderately red from 0.5 to 0.7 ṳm, and show a strong near-infrared absorption feature centered around 0.95 ṳm. Surface composition may be similar to basaltic achondrites.

X-type – a collection of several asteroid classifications with similar spectra, but probably quite different compositions.

D-type – an asteroid type that is rare in the main belt, but becomes increasingly dominant beyond the 2:1 Jovian resonance. Their spectra are neutral to slightly reddish shortward of 0.5 ṳm, very red longward of 0.55 ṳm, and for some objects the spectrum tends to flatten longward of 0.95 ṳm. Coloring may be due to kerogen-like materials.

(Binzer et al. 1989)

Results

This project extracted 2,150 asteroids with 10+ observations from a catalog of 471,569 moving objects. Then the SORTEDSDSS program removes contaminated data points and solves for phase slope, G, and H. Next, the u'g'r'i'z' SDSS colors were compiled to plot taxonomy. In the following figures, there is an interesting correlation of phase behavior with semi-major axis detected, which has not been seen before.

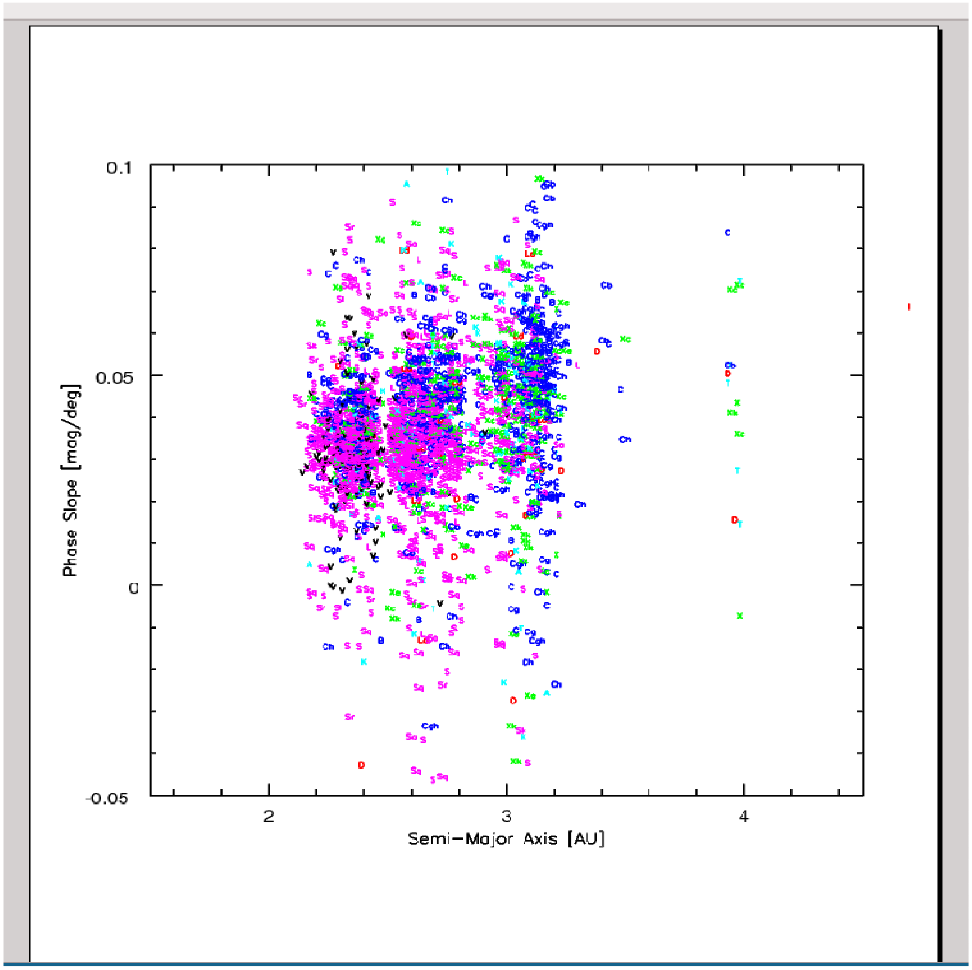

Figure 6 – This plot shows the solar phase as a function of semi-major axis. As expected, a running mean of solar phase coefficient is strongly correlated with orbital elements, with the inner main-belt dominated by bright S-type asteroids and transitioning to darker C and D-type asteroids with steeper solar phase slopes. The trend is that steeper slopes tend to be at further heliocentric distances.

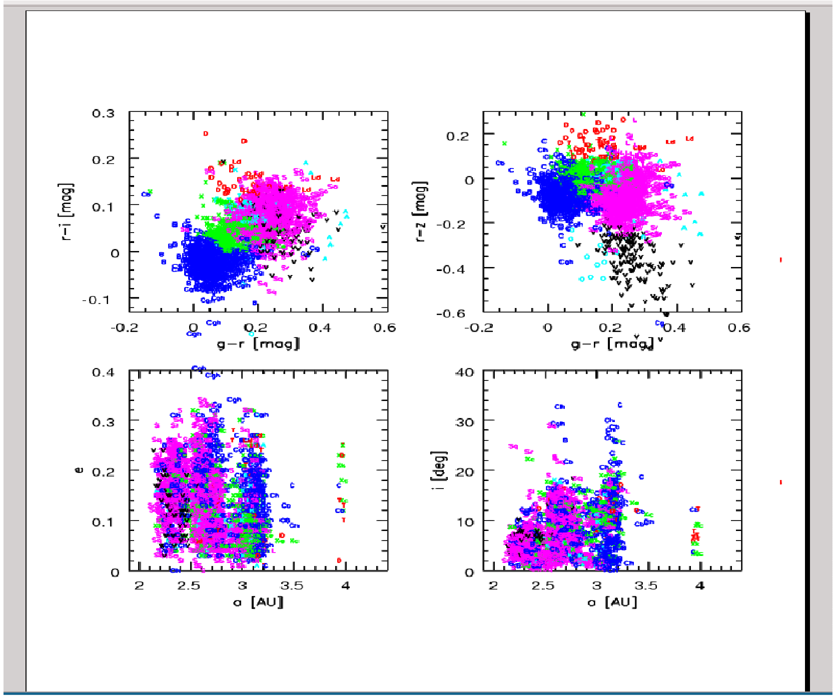

Figure 7 – These top two plots show the clumping of similar taxonomic types that we can see with the colors. The bottom two plots eccentricity with semi-major axis and inclination with semi-major axis.

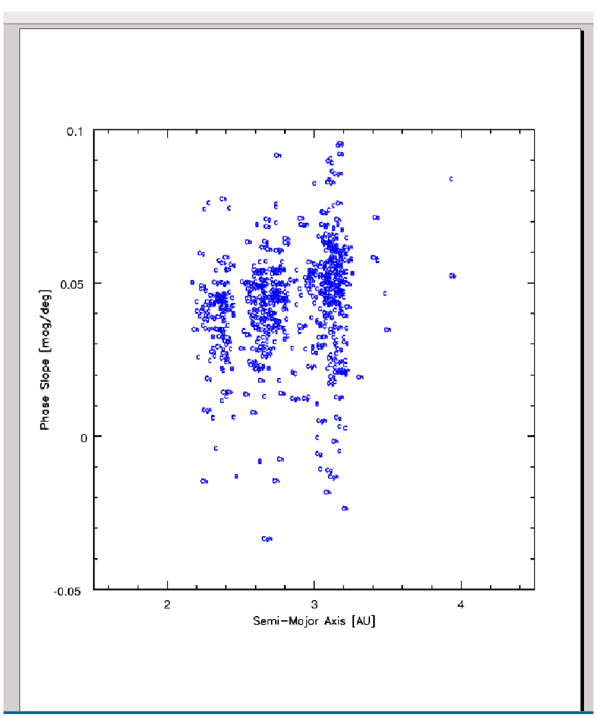

Figure 8 – C-type asteroids

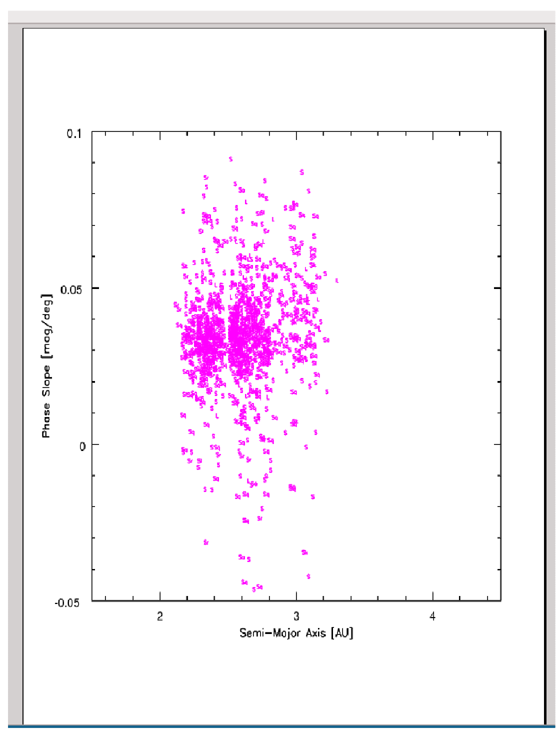

Figure 9 – S-type asteroids

From figures 8 & 9, the two types that we see clearly having a linear trend would be in the c and s-type asteroids.

Future Plans

Additional work will be done to calculate phase slopes as well as more refined G values. Then we shall discuss errors induced by the standard "G=0.15" assumption made in absolute magnitude determination, which may slightly affect number-size distribution models.

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