

# SURFACE CHARACTERISTICS OF NEAR-EARTH OBJECTS

by

NANCY P. HSIA

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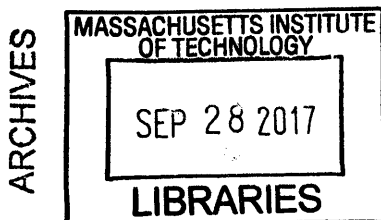
Department of Physics  
May 9, 2003

Certified by \_\_\_\_\_ **Signature redacted**

Richard P. Binzel  
Professor of Planetary Sciences  
Thesis Supervisor

Accepted by \_\_\_\_\_ **Signature redacted**

J. Brian Evans  
Department Thesis Coordinator



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## Abstract

Asteroids are thought to be the source of all meteorites found on Earth. Numerous spectroscopic studies have been performed to try and link certain types of meteorites with certain classes of asteroids in space. However, these spectroscopic studies of meteorites and asteroids have often shown a discrepancy between the meteorite and asteroid spectra, with the asteroid spectra showing a higher red slope and less prominent absorption bands. This effect has been seen especially in the spectra of asteroids located in the main belt. Scientists now believe that space weathering processes, such as solar wind ion implantation and bombardment by micrometeorites, can affect the upper few millimeters of an asteroid's surface to produce the higher red slope and reduced absorption bands seen in spectra. However, asteroids in the near-Earth region, which are generally smaller than those found in the main belt, have not shown signs of space weathering as much as asteroids in the main belt.

The purpose of this study was to investigate factors that might influence the appearance of near-Earth asteroid spectra, in particular the conditions at the time of observation. The two main observational conditions examined were the apparent magnitude of the object, or V-magnitude, and the angle between the Earth, object, and Sun, commonly called the Phase Angle. Running-box average plots and least-squares analysis was performed on a data set of 332 near-Earth asteroids to determine if any links could be made between the spectral characteristics and observational parameters.

The most interesting finding of this study was a correlation in the SQ-complexes between the second spectral component, PC2', which indicates the presence or absence of an absorption band at  $1\mu\text{m}$ , and the Phase Angle for the SQ-complex asteroids, suggesting that the observation

angle affects the spectrum of an asteroid. One possible explanation may lie in the fact that the particle size of the asteroid surface must be much larger than the wavelength of the light to create the multiple scattering needed to reflect light in the direction of the Earth.

**Table of Contents**

Abstract ..... 2

List of Figures ..... 5

1. Introduction ..... 6

2. Data Reduction ..... 12

3. Results ..... 24

4. Discussion ..... 26

5. Conclusions ..... 30

6. References ..... 32

7. Acknowledgements ..... 33

## List of Figures

1. Meteorite Classes .....	7
2. Running-box average plot (box size = 20) of Slope versus H-magnitude for more than 2000 asteroids in the main belt and near-Earth region from the SMASS data set .....	10
3. Running-box average of Slope versus running-box average of Phase Angle for the S-complex, box-size of 5 .....	13
4. Running-box average of PC2' versus running-box average of Phase Angle for the Q-complex, box-size of 5 .....	14
5. The least-squares line for Slope versus H-magnitude for the SQ-complexes .....	17
6. The least-squares line for Slope versus H-magnitude for the S-complex .....	18
7. The least-squares line for Slope versus H-magnitude for the Q-complex .....	19
8. The least-squares line for Slope versus H-magnitude for the X-complex .....	20
9. The least-squares line for Slope versus V-magnitude for the Q-complex .....	21
10. The least-squares line for PC2' versus Phase Angle in the SQ-complexes .....	22
11. The least-squares line for PC2' versus Phase Angle in the Q-complex .....	23
12. The least-squares line for PC2' versus Phase Angle in the S-complex .....	24
13. The Bus Taxonomy (2002) of PC2' versus Slope for different asteroid complexes .....	27
14. Harris and Lupishko (1989) plot illustrating the dependence of an asteroid's magnitude on its phase angle at the time of observation .....	28
15. The multiple scattering of light by rough surfaces compared to the single scattering of light by a smooth surface .....	29

## 1. Introduction

Asteroids are small rocky bodies that were formed at the same time as the planets of our solar system. Gravitational perturbations in the area surrounding the asteroids, however, prevented the small bodies from coalescing into a larger planet (Chapman, 1999) and so they remain today in their primitive state, providing important clues about our solar system's origins and early composition.

The main reservoir of asteroids lies between the orbits of Mars and Jupiter, at a distance of approximately 1.5 to 5 AU. The main belt is a collection of over 50,000 known small rocky bodies that did not combine into a planet due to Jupiter's large gravitational perturbations. Another group of asteroids, known as the Trojans, orbit at Jupiter's  $L_4$  and  $L_5$  Lagrangian points (Bottke, 2002), a distance of approximately 5.2 AU (Chapman, 1999). Some asteroids are found outside these two main asteroid reservoirs, with perihelion distances  $q \leq 1.3$  AU. These are called near-Earth asteroids. Other objects that are found in the near-Earth region include extinct comets, interplanetary dust particles, interstellar dust particles, and human-made space junk (Binzel, 2002). Collectively, these bodies are known as near-Earth objects (NEOs).

The number of known NEOs is currently around 1000 and continues to grow with surveys such as LINEAR, LONEOS and NEAT that specifically search for NEOs. One reason people are interested in finding and tracking NEOs is the possibility of a large asteroid colliding with the earth and devastating much of the planet. However, scientists are also interested in NEOs because they are a source of meteorites (Bottke, 2002).

Meteorites are small bodies that have fallen to Earth and range from a few millimeters to a few hundred meters in size. They are assumed to be pieces of asteroids that have reached Earth after a series of collisions in outer space breaks up the parent asteroid into smaller pieces. These

small asteroid pieces eventually fall into orbital resonance with Jupiter. For instance, if a body orbits the Sun three times in the time that it takes Jupiter to orbit the Sun once, it is in a 3:1 resonance. This particular resonance, along with several others, such as the 2:1 and 5:2 orbital resonances, and the v6 secular resonance, are the main resonances that eject pieces of asteroids out of the main belt into an Earth-crossing orbit. These asteroid pieces can eventually collide with Earth and fall to the Earth's surface as meteorites (Chapman, 1999; Hartmann, 1999; Scholl, 1989).

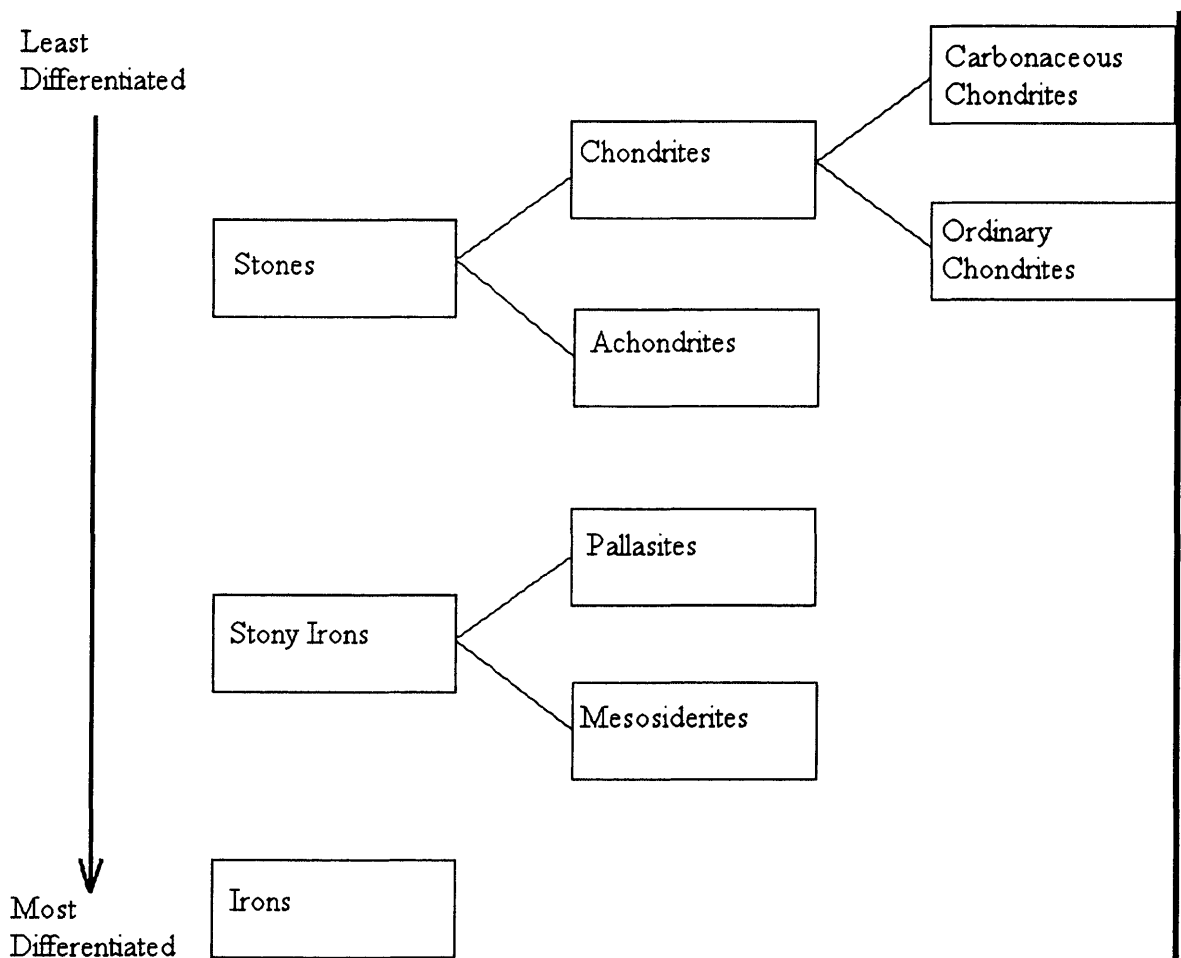


Figure 1. Meteorite Classes. The three main classes of Stones, Stony Irons, and Iron meteorites are further sub-divided depending on the composition of the meteorite. The least differentiated meteorites are at the top of the figure, and the most differentiated meteorites are at the bottom.

Meteorites are categorized by composition into three main classes, Stones, Stony Irons, and Irons. The classes can be further subdivided depending on the amount of differentiation a meteorite has experienced (see Figure 1). The most primitive bodies, which are the least heated and are undifferentiated, are carbonaceous chondrites. These are followed by ordinary chondrites, which have undergone a moderate amount of heating. Achondrites are highly differentiated meteorites in the Stone group. The Stony Iron group consists of differentiated meteorites, pallasites and mesosiderites, that exhibit a mix of iron metal and stone. The most differentiated group of meteorites is the Iron group (Hartmann, 1999).

Asteroids are also classified into different types, depending on the appearance of their spectra. The Bus and Binzel taxonomy (Bus and Binzel 1, 2002), which is based on the standard Tholen taxonomy, defines 26 different types of asteroids by analyzing features seen in the spectra and comparing each asteroid spectrum to other similar spectra.

Spectroscopic studies of asteroids and meteorites have shown similarities between specific groups of meteorites and asteroids. These similarities are based on the slope of the visible wavelength spectrum as well as the presence or absence and strength of a mineral absorption band near one micron. For instance, the spectra of basaltic achondrite meteorites bear a strong resemblance to the spectra of V-type asteroids (Clark, 2002).

Other similarities in spectra have been observed for A-type asteroids and pallasites, C-type asteroids and carbonaceous chondrites, and a few Q-type asteroids and ordinary chondrites (Clark, 2002; Chapman, 1999). However, until recently scientists have found very few Q-type asteroids. The ordinary chondrites are the most abundant type of meteorite, while the S-asteroids are the most common type of asteroid. It would seem that they are related based solely on account of their numbers, but spectral links have been difficult to make. In many cases, even



within those matches that have already been made (Clark, 2002), the meteorite spectra do not always exactly match the asteroid spectra, and the cause of this spectral change is now believed to be due to the phenomenon called space weathering (Clark, 2002).

Space weathering refers to any process that changes the apparent spectroscopic traits of an airless body, such as collisions, solar-wind ion implantation, sputtering, and micrometeorite impacts (Bottke, 2002). All of these processes may affect an asteroid's regolith so that its spectrum appears different than if it had not undergone space weathering. The main effect of space weathering is to shift a spectrum towards the red, so that an object appears “redder” than it would if it had not undergone space weathering. This is clearly seen by an increase in the overall slope of a spectrum. Space weathering also creates shallower absorption bands in spectra (Clark, 2002).

The main process behind space weathering seems to be the deposition of submicroscopic metallic iron (SMFe) particles on grain surfaces through solar wind sputtering and micrometeorite bombardment (Clark, 2002). Micrometeorites hitting an asteroid surface liberate oxidized iron present in the upper few millimeters of the asteroid's surface. The heat of these impacts transforms the iron into a metallic state, whereby this vaporized metallic iron has the opportunity to coat silicate grains present in the asteroid regolith. Meteorites, because of their entry through—and often breakup in—the Earth's atmosphere, are stripped of any regolith. Also, meteorites measured in the laboratory are often freshly ground samples and therefore do not show the effects of SMFe. It has been found that the addition of as little as 0.025% in the amount of reduced iron deposited on a meteorite sample in the laboratory can change its spectral slope sufficiently to resemble that of an S-asteroid (Clark, 2002).

Present spectroscopic studies of asteroids seem to indicate that smaller NEOs have less red spectral slopes than larger NEOs. Figure 2 shows a running-box plot of Slope versus H-magnitude for approximately 2000 S- and Q-type asteroids in the main belt and near-Earth regions. The Slope indicates the redness of the object, and thus how much it has been space weathered. The H-magnitude indicates the size of the object: larger magnitude values correspond to larger objects. Figure 2 shows that the Slope tends to be higher for the

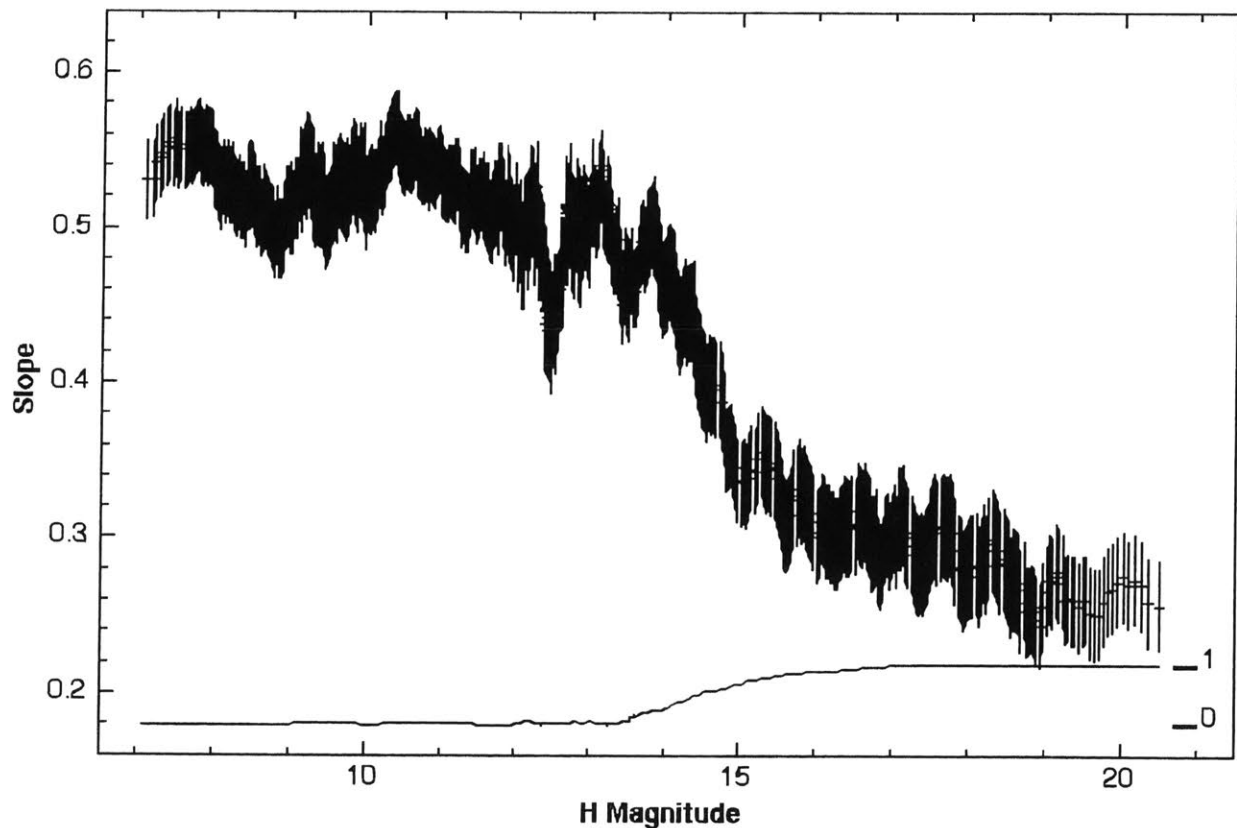


Figure 2. A running-box average plot (box size = 20) of Slope versus H-magnitude for more than 2000 asteroids in the main belt and near-Earth region from the Small Main-belt Asteroid Spectroscopic Survey. This plot shows a correlation between Slope and object size (larger H-magnitude implies larger size). The line at the bottom of the plot indicates the fraction of near-Earth objects in the sample. The fraction of near-Earth objects increases for smaller H-magnitudes. Smaller objects, which are mainly near-Earth objects, seem to have smaller Slope values than larger objects in the main belt. This suggests that smaller objects are not as space weathered as larger objects.

larger objects. The decrease in the value of Slope at H-magnitudes of 14 – 15 corresponds to an increase in the number of near-Earth asteroids, as seen by the percentage line on the lower half of the figure. The smaller near-Earth asteroids seem to be less space weathered than their main belt counterparts. This may be because smaller bodies are younger and have had less time to be affected by space weathering processes (Binzel, 2002).

It is unclear, however, if the near-Earth objects are actually less space weathered than objects in the main belt, or if the higher red slope in the spectra of main belt objects is due to an observational bias. It may be that because we have observed more small NEOs than small main-belt asteroids, we have seen both the large, space weathered objects as well as the smaller, non-space weathered objects in the near-Earth region, while we have only been able to see large, space weathered objects in the main belt.

Studies have also indicated that some types of asteroids are less susceptible to space weathering. The amount of space weathering an asteroid undergoes depends on its composition (Clark, 2002). Bright, transparent particles are affected by space weathering more than dark, opaque particles. The S-type asteroids seem to be strongly affected by space weathering, while the C-type asteroids, which are composed of dark, opaque minerals such as graphite and other carbon-based minerals (Hartmann, 1999), are affected very little. This has led to the theory that the S-type asteroids are indeed the parent bodies of ordinary chondrites, but the spectral data do not match exactly because of space weathering.

The purpose of this study is to determine whether or not the differences in spectral slope seen in some asteroid spectra, particularly those of the S-, Q-, and X-type complexes, is due to an observational bias or due to space weathering. It may be that the change in slope thought to be a space weathering effect is seen simply because of the conditions of the observation, such as the

phase angle or visual magnitude of the object in the sky. We are especially interested in how the spectra of S-type asteroids may be affected by observing parameters because it may provide insight into whether or not they are truly the parent bodies of ordinary chondrites. I compared spectral characteristics of over 300 asteroids to determine if a correlation could be found between the appearance of the spectra and the circumstances of the observation.

## **2. Data Reduction**

Spectral data of 332 near-Earth and Mars-crossing objects gathered in the Small Main-Belt Asteroid Spectroscopic Survey (SMASS) were used in this study. The slope and PC2' of the spectral data, along with other spectral characteristics, were calculated by Bus and Binzel (see Bus and Binzel 2, 2002) using principal component analysis. Principal component analysis is a mathematical technique involving linear transforms of data in space. The largest amount of variance in the data is described by the first component (PC1), while the next largest fraction is described by the second component (PC2), etc. Bus and Binzel calculated the spectral components by first removing the average slope of each spectrum, and then calculating the principal components using the covariance matrix instead of the correlation matrix. This resulted in the two spectral parameters of interest in our study: the first principal component, Slope, which indicates the redness of the spectra, and the second spectral component, PC2', which indicates the presence or absence of an absorption band at 1- $\mu\text{m}$ .

Missing information on the phase angle and V-magnitude of the asteroids in the SMASS data set were gathered by consulting Xu, the observation notebooks of Binzel, and the JPL

Ephemeris Generator. The Phase Angle is the angle from the Sun to the object to the Earth. The V-magnitude is the apparent magnitude of the object in the visible range.

I used data for the asteroids whose spectral characteristics of Slope and PC2' had already been calculated. I plotted the running-box averages of the spectral characteristics (Slope and PC2') versus the running-box averages of the observational parameters (Phase Angle, V-magnitude, and H-magnitude). This was helpful in seeing if there seemed to be a trend in the data that needed to be investigated further. An overall trend was defined as any trend larger than the size of the error bars in the data, for example a downward slope of the data points that is much larger than the size of the error bars. For example, using the data for the S-complex, I first

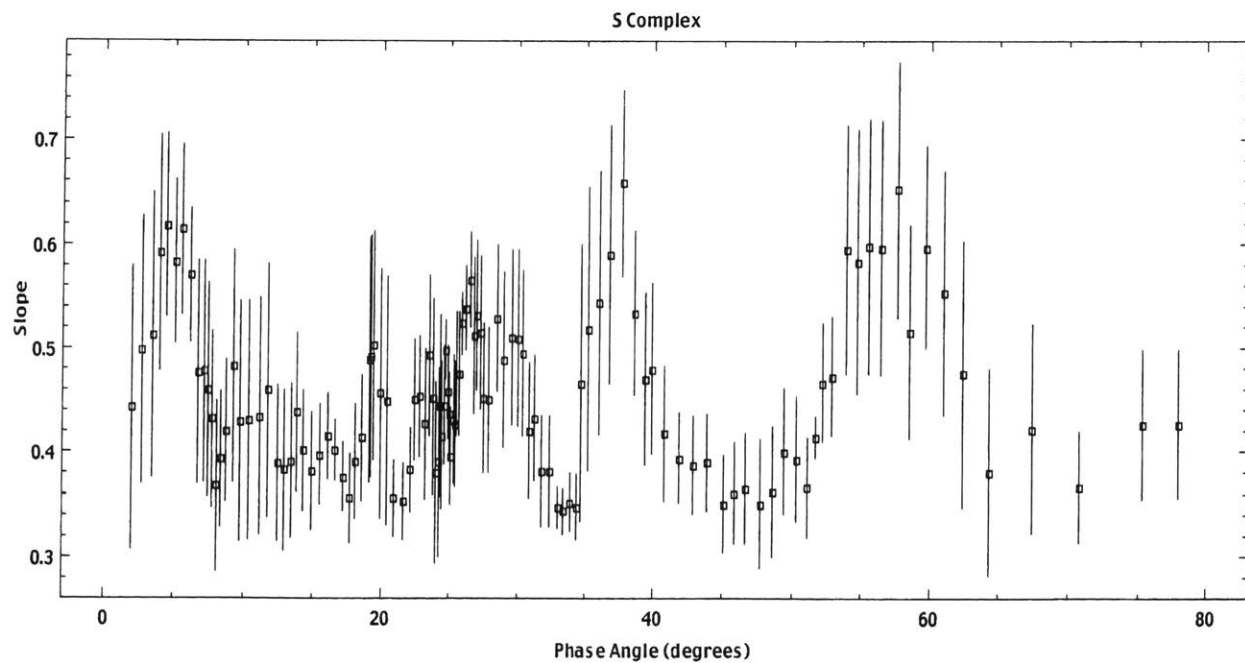


Figure 3. Running-box average of Slope versus running-box average of Phase Angle for the S-complex, box-size of 5. No overall correlation (a trend larger than the size of the error bars) can be seen in the data, and thus the correlation between Phase Angle and Slope for the S-complex was not investigated further.

sorted the data in order of ascending Phase Angle. I then calculated the running-box average for the Slope using a box size of 5 and plotted these values versus the running-box average for the Phase Angle, again using a box size of 5. The resulting plot can be seen in Figure 3.

In this case, there is no overall trend in the data, and so it was assumed that there was no correlation between Slope and Phase Angle for the S-complex. An example of a plot that showed a trend is seen in Figure 4, where the running-box average plot for PC2' and Phase Angle in the Q-complex shows a slight downward slope for the larger Phase Angles.

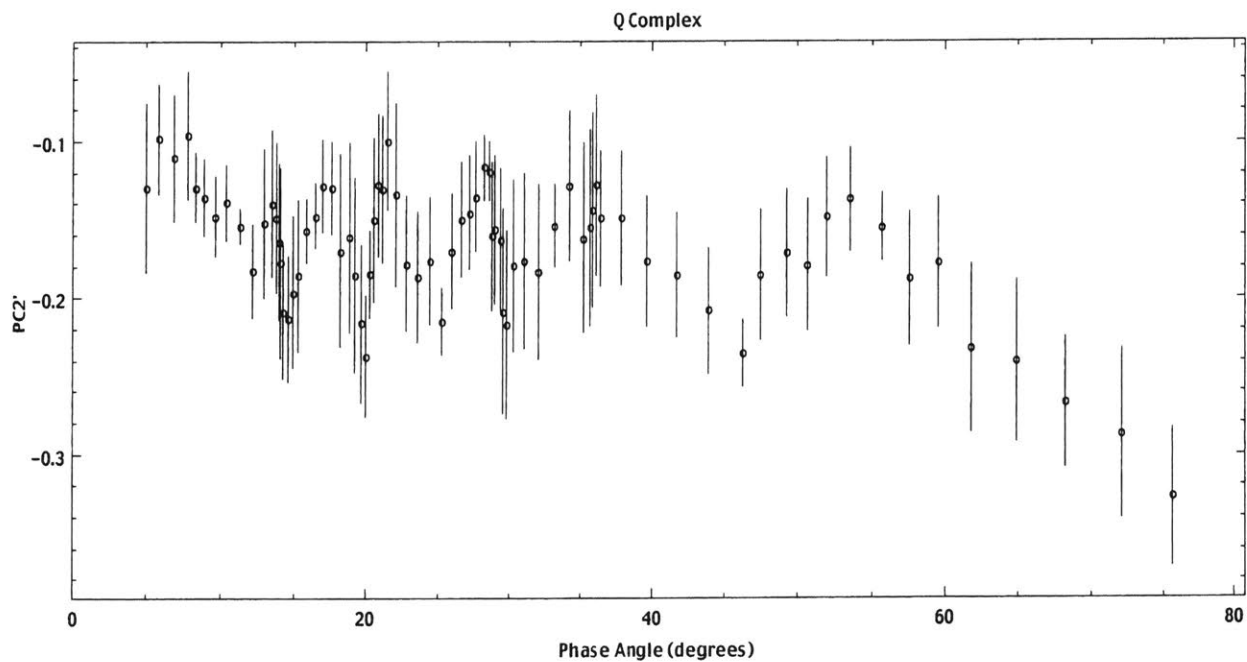


Figure 4. Running-box average of PC2' versus running-box average of Phase Angle for the Q-complex, box-size of 5. The plot shows an overall downward slope in the data, suggesting a correlation between PC2' and Phase Angle in the Q-complex. This correlation was further investigated using least-squares line fitting.

All of the spectral characteristics and observational parameters that were examined using the running-box average plot method can be seen below in Table 1.

**Table 1. Summary of Correlation Investigation**

<b>Asteroid Complex</b>	<b>X-variable</b>	<b>Y-variable</b>	<b>Correlation Seen?</b>
S and Q	Phase Angle	Slope	No
	Phase Angle	PC2'	Yes
S and Q	V-magnitude	Slope	No
	V-magnitude	PC2'	No
S and Q	H-magnitude	Slope	Yes
	H-magnitude	PC2'	No
Q	Phase Angle	Slope	No
	Phase Angle	PC2'	Yes
Q	V-magnitude	Slope	Yes
	V-magnitude	PC2'	No
Q	H-magnitude	Slope	No, but still analyzed
	H-magnitude	PC2'	No
S	Phase Angle	Slope	No
	Phase Angle	PC2'	No, but still analyzed
S	V-magnitude	Slope	No
	V-magnitude	PC2'	No
S	H-magnitude	Slope	Yes
	H-magnitude	PC2'	No
C	Phase Angle	Slope	No
	Phase Angle	PC2'	No
C	V-magnitude	Slope	No
	V-magnitude	PC2'	No
C, S, and Q	V-magnitude	Slope	No
X	Phase Angle	Slope	No
	Phase Angle	PC2'	No
X	V-magnitude	Slope	No
	V-magnitude	PC2'	No
X	H-magnitude	Slope	Yes
	H-magnitude	PC2'	No

An examination of the running-box average plots revealed trends in six plots. The correlations between these variables were further investigated using the least-squares fitting method. The

correlations investigated were the correlation between PC2' and Phase Angle in the SQ-complex, the correlation between PC2' and Phase Angle in the Q-complex, the correlation between Slope and V-magnitude in the Q-complex, the correlation between Slope and H-magnitude in the X-complex, the correlation between Slope and H-magnitude in the SQ-complex, and the correlation between Slope and H-magnitude in the S-complex. Though no trend was clearly seen between H-magnitude and Slope for the Q-complex, these variables were also investigated because of the SQ-complex correlation seen between these variables. Similarly, the least-squares analysis was also performed to determine if there was a correlation between Phase Angle and PC2' in the S-complex.

The least-squares line was calculated along with the linear correlation coefficient,  $r$ . The least-squares line was fit to the original spectral component data points, not the running-box average of the spectral component. The least-squares lines for each of the eight correlations analyzed can be seen below in Figures 5 – 12, with the findings summarized in Table 2.

**Table 2. Spectral Components and Observational Parameters Analyzed with Least-Squares Fitting**

Figure Number	Asteroid Complex	X-var.	Y-var.	Number of Data Points	$r$ -value	Confidence level	Significant ?
5	SQ	H-magnitude	Slope	202	0.257	5%	Yes
6	S	H-magnitude	Slope	121	0.251	5%	Yes
7	Q	H-magnitude	Slope	81	0.087	5%	No
8	X	H-magnitude	Slope	43	0.423	5%	Yes
9	Q	V-magnitude	Slope	81	0.166	5%	No
10	SQ	Phase Angle	PC2'	202	0.285	5%	Yes
11	Q	Phase Angle	PC2'	81	0.353	5%	Yes
12	S	Phase Angle	PC2'	121	0.272	5%	Yes



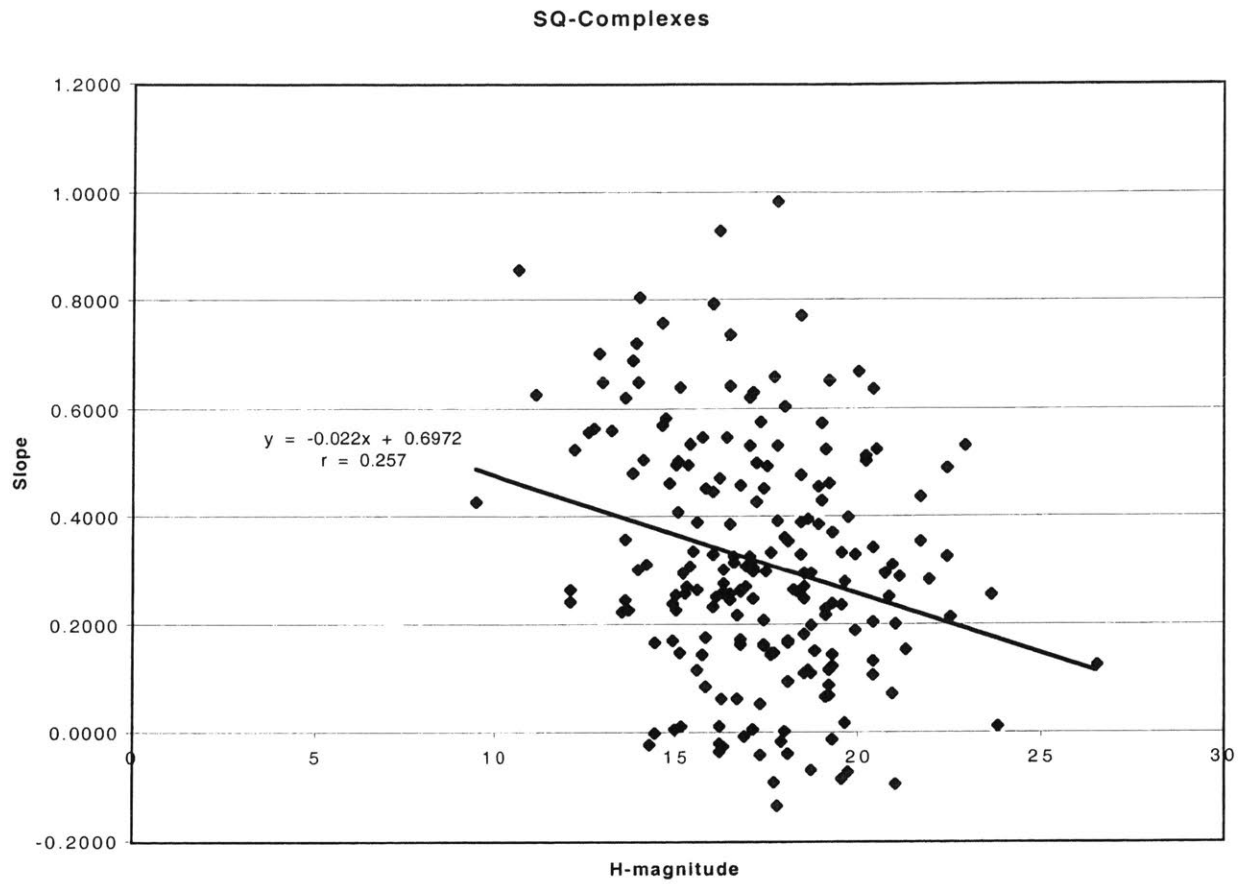


Figure 5. The least-squares line for Slope versus H-magnitude for the SQ-complexes. The correlation coefficient is  $r = 0.255$ , which is significant at the 5% level.

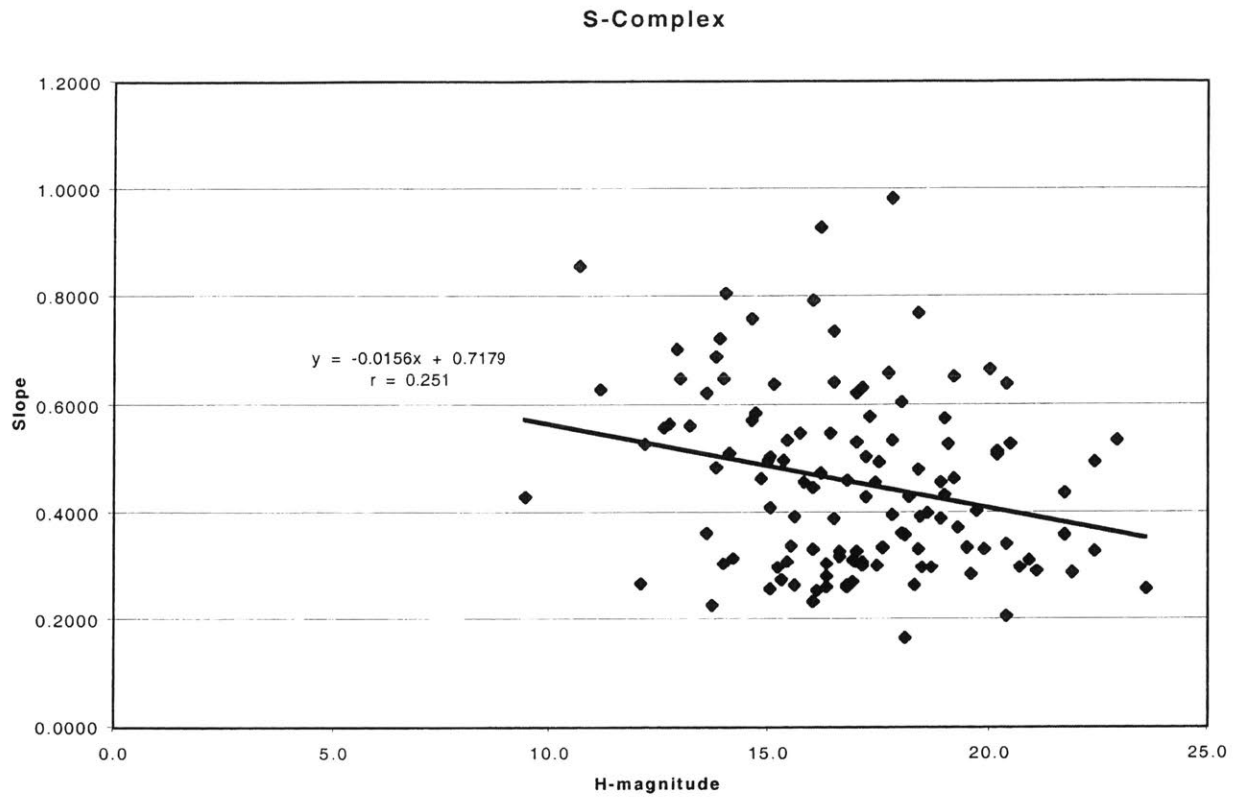


Figure 6. The least-squares line for Slope versus H-magnitude for the S-complex. The correlation coefficient is  $r = 0.251$ , which is significant at the 5% level.

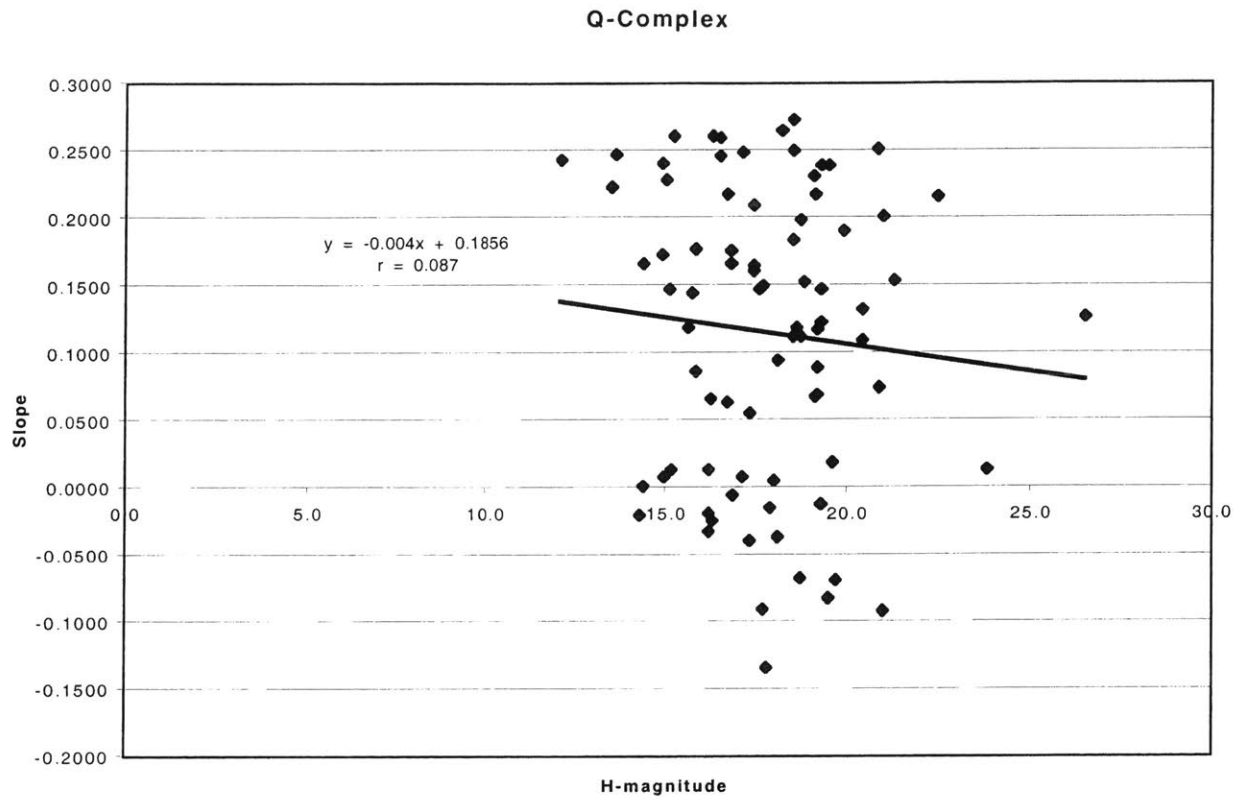


Figure 7. The least-squares line for Slope versus H-magnitude for the Q-complex. The correlation coefficient is  $r = 0.087$ , which is not significant at the 5% level.

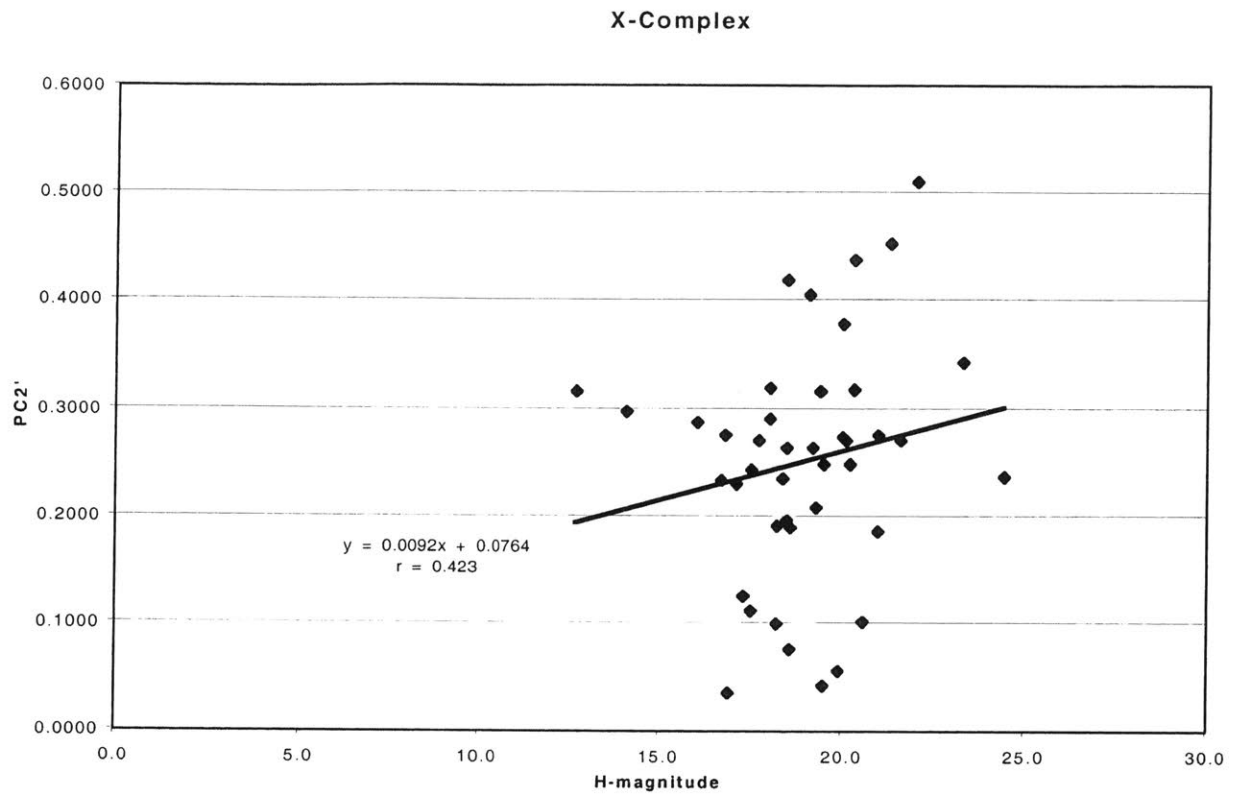


Figure 8. The least-squares line for Slope versus H-magnitude for the X-complex. The correlation coefficient is  $r = 0.423$ , which is significant at the 5% level.

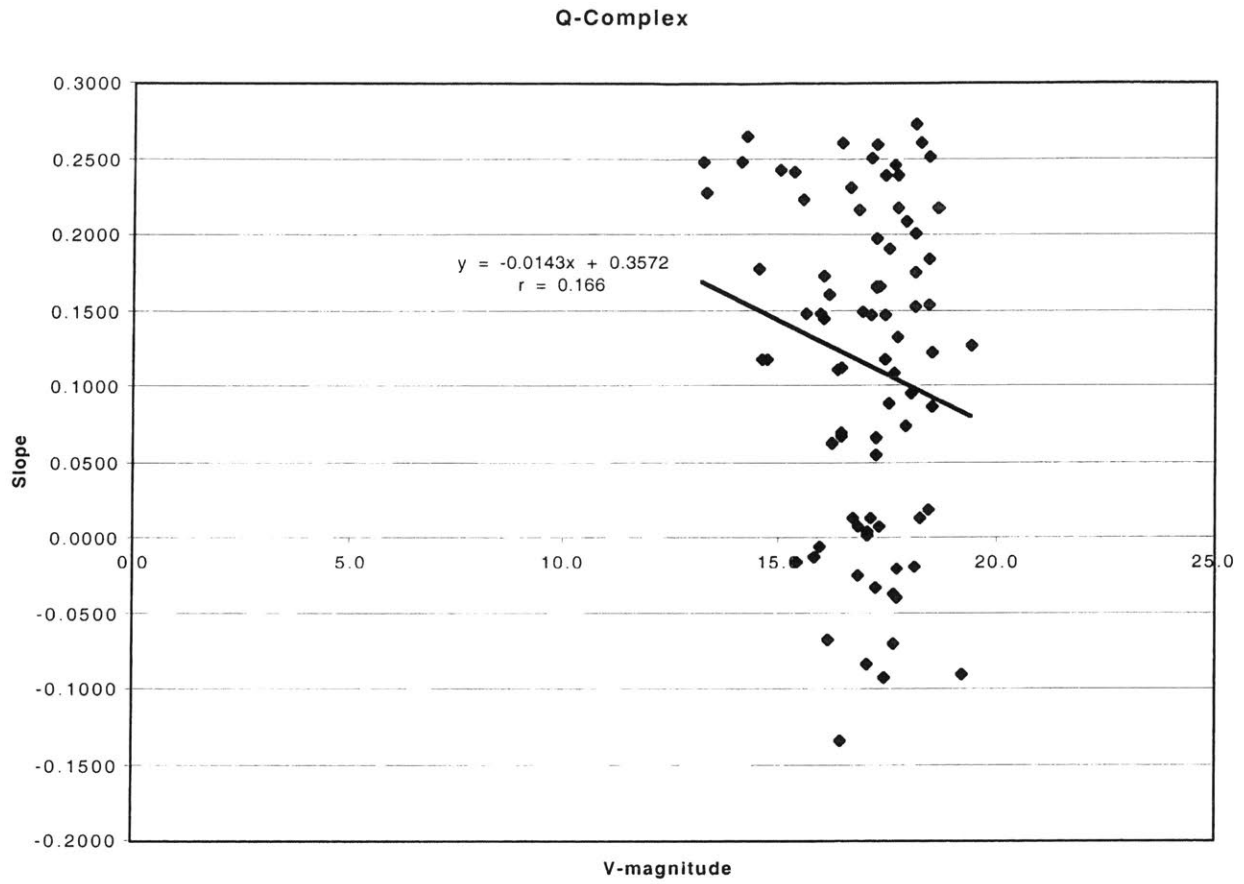


Figure 9. The least-squares line for Slope versus V-magnitude for the Q-Complex. The correlation coefficient is  $r = 0.166$ , which is not significant at the 5% level.

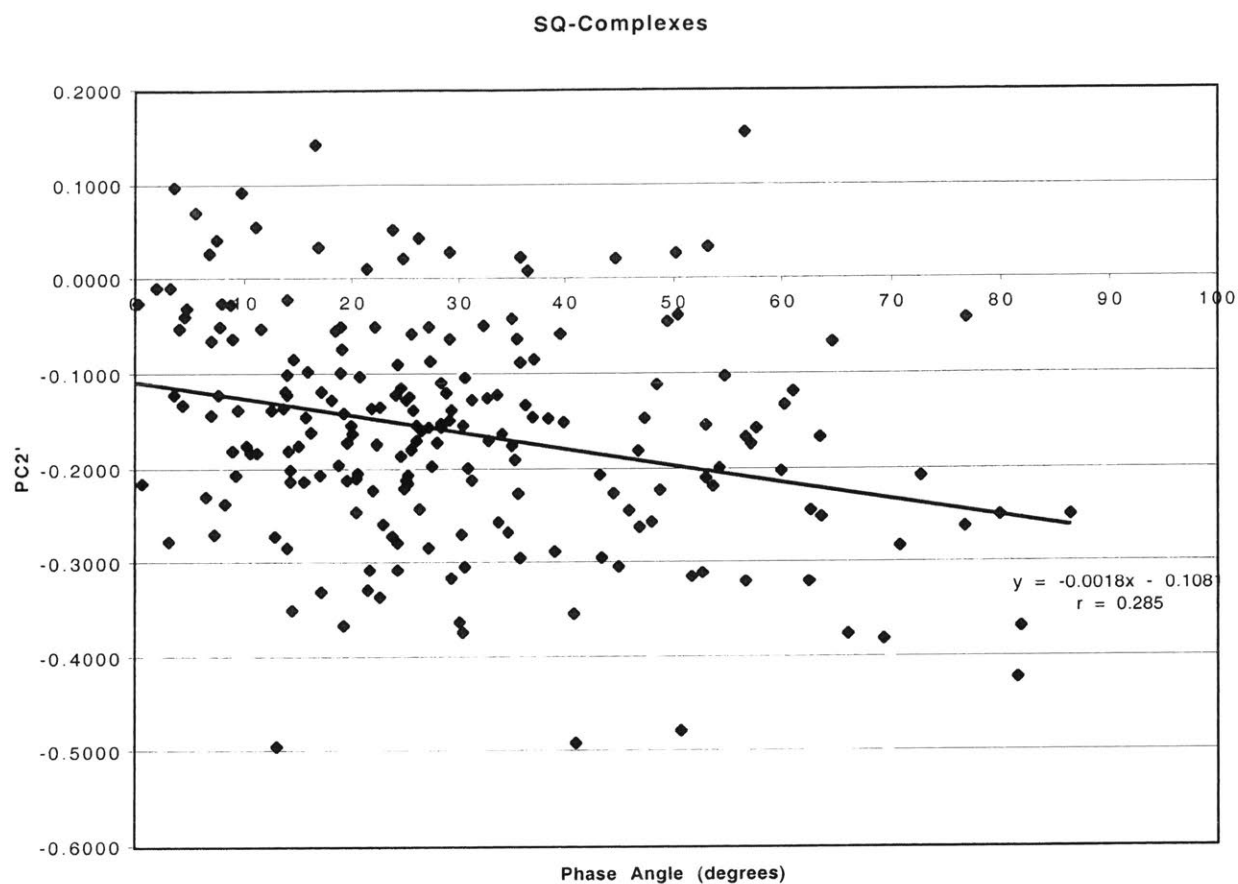


Figure 10. The least-squares line for PC2' versus Phase Angle for the SQ-complexes. The correlation coefficient is  $r = 0.285$ , which is significant at the 5% level.

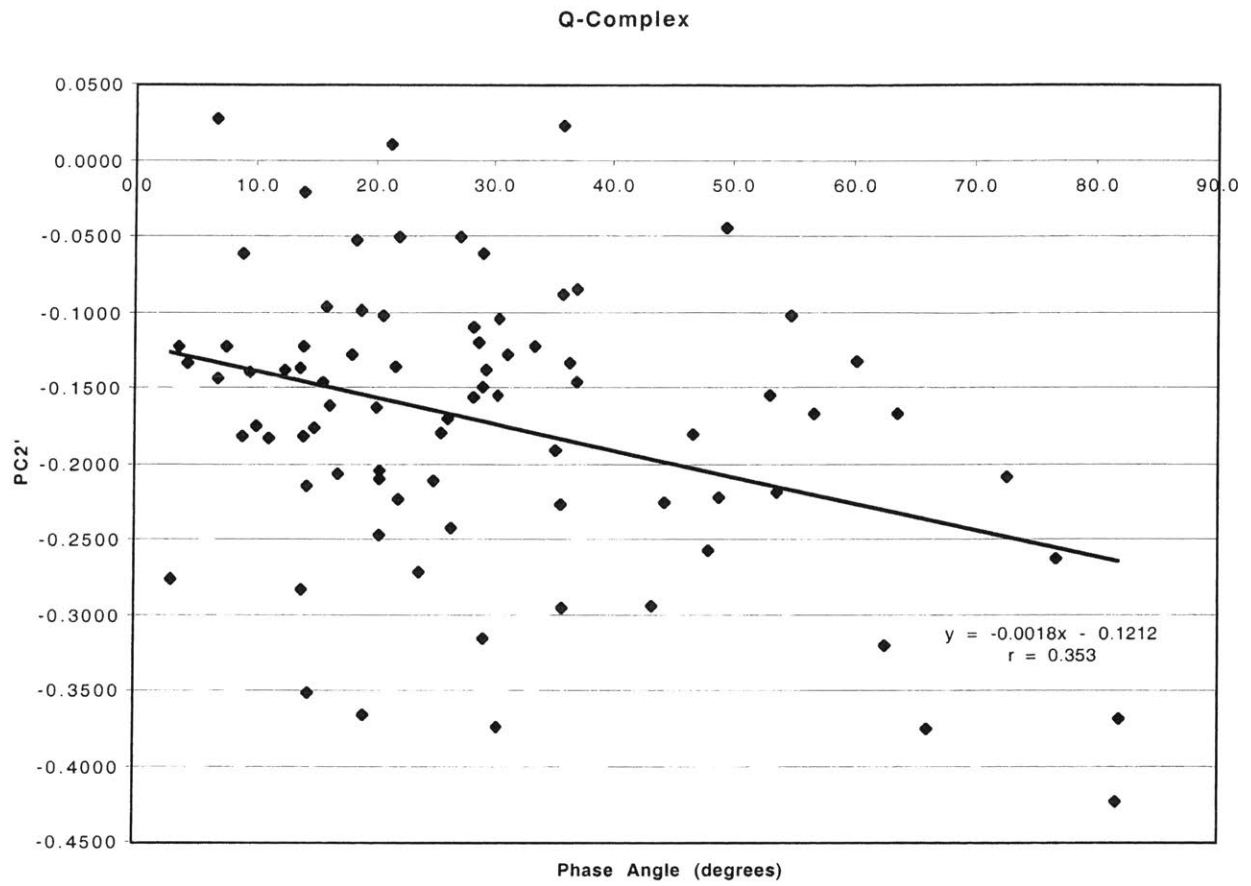


Figure 11. The least-squares line for PC2' versus Phase Angle for the Q-complex. The correlation coefficient is  $r = 0.353$ , which is significant at the 5% level.

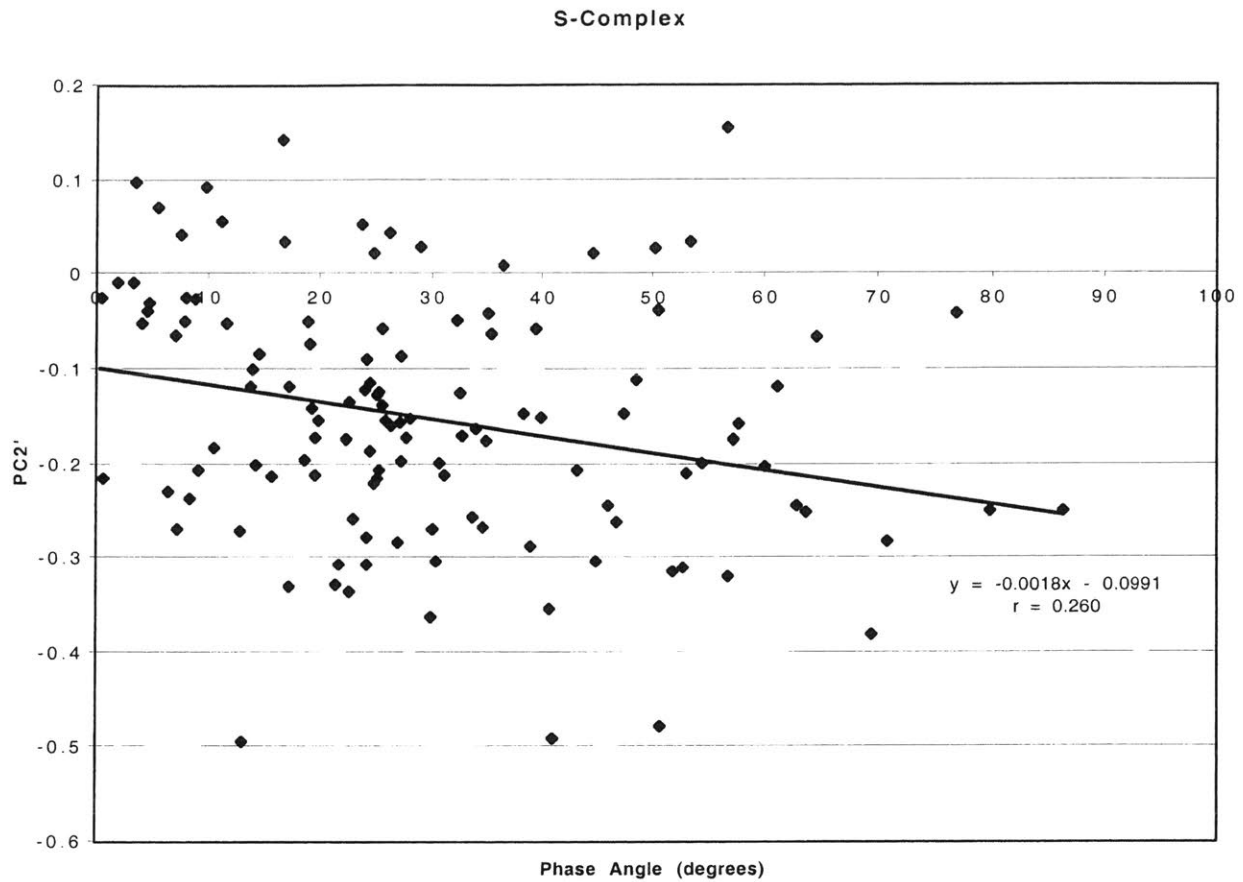


Figure 12. The least-squares line for PC2' versus Phase Angle for the S-complex. The correlation coefficient is  $r = 0.260$ , which is significant at the 5% level.

### 3. Results

The majority of the running-box average plots did not indicate a correlation between the variables. However, eight of the plots were further investigated with a least-squares fit line to determine whether or not a correlation existed between the variables (see Table 2). The correlation coefficient value was compared to a table of significant correlation coefficient values to find the percent chance that two uncorrelated variables would show a similar amount of correlation (see Taylor, 1997).



There was a real correlation found between the Slope and H-magnitude for the S- and Q-complexes combined (Figure 5) and for the S-complex on its own (Figure 6). The correlation coefficient value for the S- and Q-complexes ( $N = 202$ ) was  $r = 0.255$ , which indicates a high correlation of at least 98.8% chance that the two variables are correlated. The correlation coefficient  $r = 0.25$  was also statistically significant at the 5% level for the S-complex ( $N = 121$ ). However, no correlation was found (Figure 7) between the two variables for the Q-complex on its own ( $r = 0.09$ ,  $N = 81$ ), suggesting that the S-complex is solely responsible for the Slope and H-magnitude correlation seen in the SQ-complex plot. The X-complex (Figure 8) correlation coefficient value of  $r = 0.2$  ( $N = 43$ ) was not significant at the 5% level.

The running box average plot for the Q-complex seemed to indicate a correlation between Slope and V-magnitude. The correlation coefficient value of  $r = 0.17$  (see Figure 9) was not significant at the 5% level.

Figure 10 shows the least-squares line correlation coefficient between PC2' and Phase Angle for the SQ-complexes was  $r = 0.27$ , which was significant at the 5% level for  $N = 202$ . In Figure 11, the correlation between PC2' and Phase Angle for the Q-complex was  $r = 0.35$  which was significant at the 5% level for  $N = 81$ . There was also a fairly high correlation for PC2' and Phase Angle in the S-complex (Figure 12), with an  $r = 0.27$ . However, there was no trend seen in the running-box plot for these two variables. It may be that the correlation in the S-complex is due more to the high number of data points, while the Q-complex correlation is actually more significant for the overall correlation seen in the SQ-complexes.

#### 4. Discussion

The trend between Slope and H-magnitude discussed in the Introduction and seen in Figure 2 does seem to be a real correlation for the SQ-complexes, based on the correlation coefficients found in the least-squares analysis. The correlation coefficient of  $r = 0.255$  for the SQ-complexes was significant at the 5% level and implies that there is a true size-dependence for Slope in the S-complex. It seems that space weathering does occur more on larger objects. The question remains as to what the causes of this size and space-weathering correlation are, as no correlations were seen between Slope and any other variables in the running-box plots.

A theory proposed by Binzel (2002), suggests that the size of the object relates to the age of the object, with smaller objects representing fresher surfaces. Smaller objects have shorter survival lifetimes, because they are often destroyed by collisions within a few million years. The longer that an object survives in space, the more space weathering it is able to undergo. Younger surfaces have had less time to be affected and show signs of space weathering than older, larger objects. There was no correlation found for the X-type objects or the Q-type objects on their own, but this is perhaps because there were not enough data points to find a correlation that was significant at the 5% level.

A more interesting result was found in Figures 10 – 12, where the relationship between PC2' and Phase Angle was analyzed for the S- and Q-complexes. The vertical spread in PC2' as seen by the least-squares line is approximately 0.1 over the entire Phase Angle range for the SQ-complexes (Figure 10). When compared with Figure 13, this suggests that the spread in PC2' for the SQ-complexes can be explained in part by the differences in Phase Angle at the time of observation. More importantly, we can ask whether or not the newly found phase angle effect on PC2' has a significant influence on the taxonomic category assignment in the Bus

taxonomy system. Fortunately, the answer appears to be “no” since the overall spread in PC2’ within both the S- and Q-complexes is 3 to 4 times larger than the average effect caused by the varying phase angle.

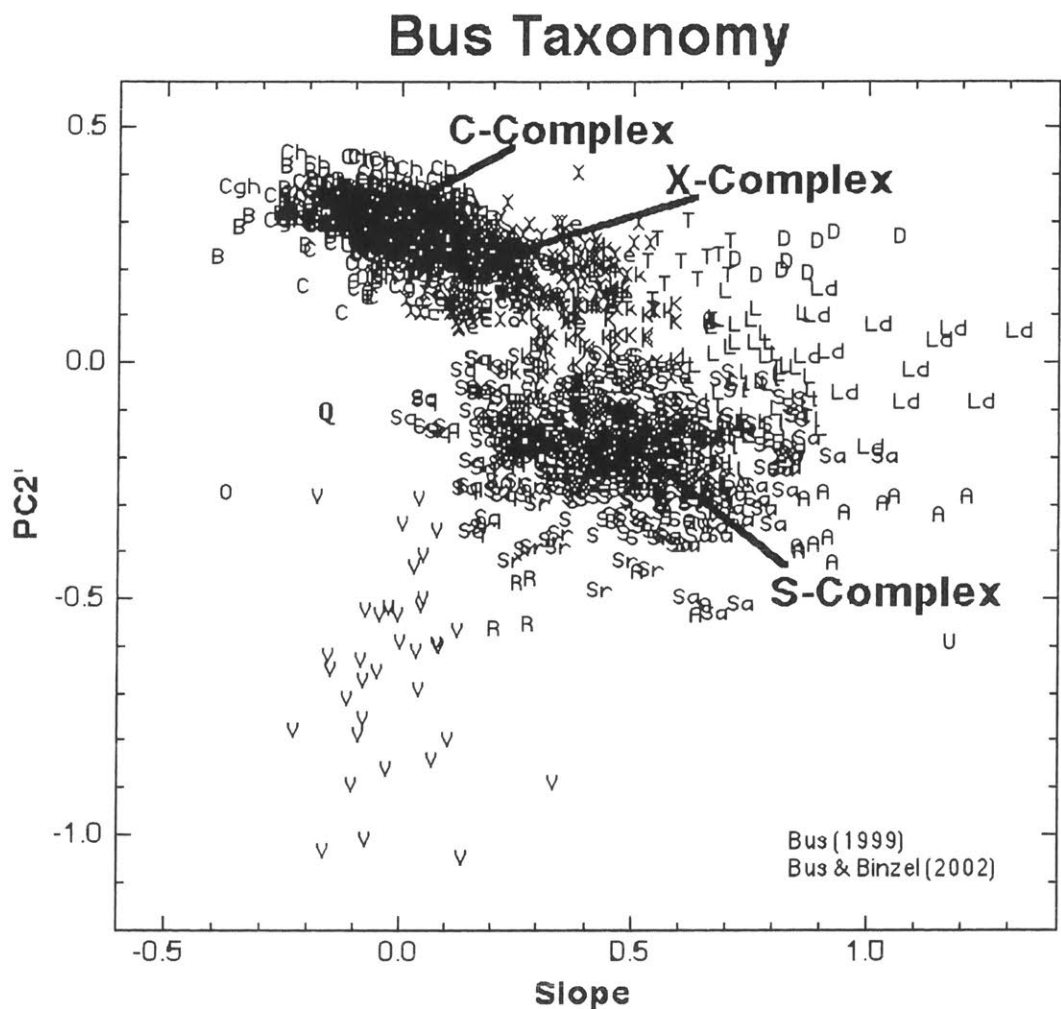


Figure 13. The Taxonomy plot made by Bus and Binzel (2002) showing the PC2’ versus Slope for different asteroid complexes. The Q-complex, which includes mainly Sq-type objects, is located on the left edge of the S-complex area. The spread in PC2’ for the Sq-type objects is from approximately 0 to -0.4. In Figure 10, a dependence of PC2’ on Phase Angle is seen for the SQ-complexes, with an average effect of about 0.1 change in PC2’ depending on Phase Angle. This spread, which is smaller than the total spread seen here, indicates that some of the spread seen here in the SQ-complexes may be due to a dependence on Phase Angle.

A possible explanation for why the Phase Angle at the time of observation would affect the PC2' spectral component requires an examination of the physics of scattering. To an asteroid, the Sun would always be seen as overhead. The amount of light reflected by the asteroid towards the Earth, however, depends on the position of the Earth in relation to the Sun.

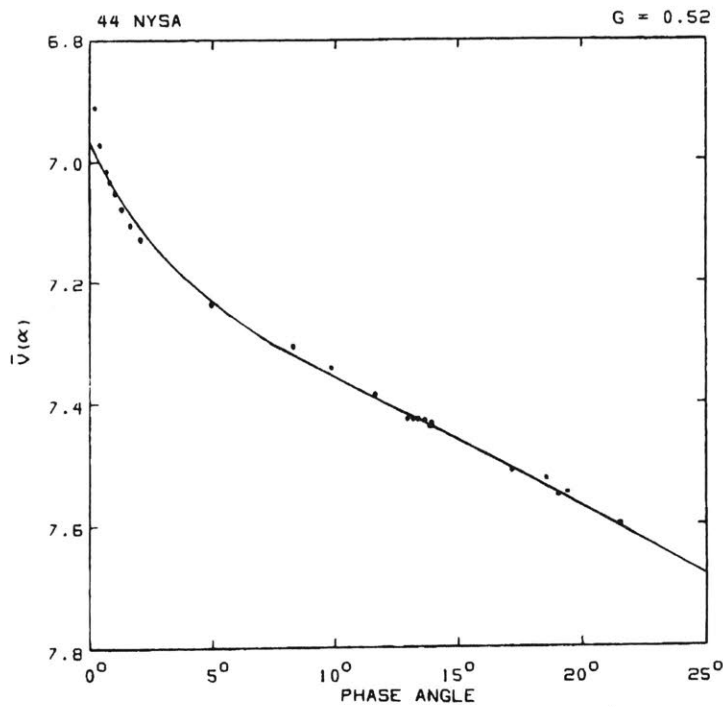


Figure 14. A plot from Harris and Lupishko (1989) demonstrating the dependence of an asteroid's magnitude on its phase angle at the time of observation. For larger phase angle observations, the magnitude of the asteroid decreases.

In Figure 14 we see that the magnitude, or brightness, of the asteroid depends on its phase angle at the time of observation (Harris and Lupishko, 1989). This is because if the Earth is very near to the Sun in the sky and the phase angle is thus very small, then the majority of the incident light is reflected back directly towards the source and also the Earth. Most importantly, an observer would see the body as fully illuminated. As the phase angle increases, less and less of the body appears fully illuminated and the object becomes less bright. For example, when the

Moon is Full, we see it as a complete disk in the sky. The actual position of the Moon is nearly in line with the Earth and the Sun, and the phase angle is very small. As the Moon continues through its cycle, it wanes to a Three-Quarters Moon, which we see as a half-disk in the sky. The phase angle is nearly 90 degrees at this point, and as the phase angle increases even more we see less and less of the surface of the Moon, as it wanes from a half-disk to a crescent shape. For these large phase angles, Hapke relationships provide better descriptions of the scattering effects (see Hapke, 1993).

As the phase angle increases, the amount of scattering that occurs in the direction of the observer depends on how many reflections take place on the asteroid surface before the incident light is reflected towards the Earth. If the asteroid had a perfectly scattering surface, where the particle size is much smaller than the wavelength, then the incident light reflected from the surface would be scattered in all directions equally. However, asteroids are rocky bodies, often featuring craters and regolith, and they are not perfectly scattering Lambertian surfaces. Instead,

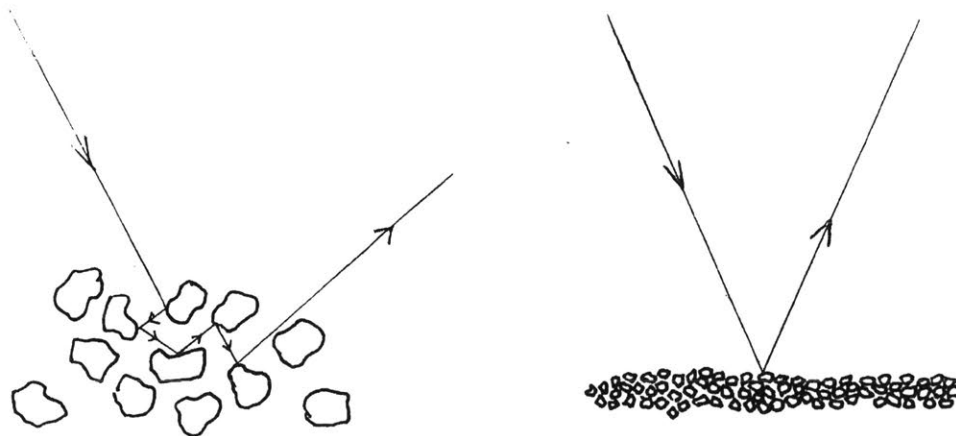


Figure 15. The multiple scattering of light by a rough surface, where the particle size is large compared to the wavelength, compared to the single scattering of light by a smooth surface, where the particle size is small compared to the wavelength.

incident light is usually reflected off of multiple particles before being reflected in the direction of the detector (see Figure 15).

These multiple reflections in the surface result in some of the light being absorbed, with two consequences. First, it decreases the total amount of light reflected towards the Earth. Second, these absorptions create the bands we see in spectrographs (Elachi, 1987). The larger the particles and the rougher the surface, the deeper an absorption band becomes because the light bounces off of more particles before being reflected. Thus, the number of reflections also directly relates to the depth of the spectroscopic bands – the more reflections, the more absorption by the surface particles, and therefore the greater the band depth. The dependence in PC2' on phase angle may therefore be due to the increase in the amount of light absorbed on the asteroid surface through multiple reflections. This implies that the asteroid's surface must be rough, in order for multiple scattering to occur in the first place. For a smooth surface, single scattering would not be expected to give any increase in absorption as a function of phase angle.

## **5. Conclusions**

It appears that there is a correlation in the SQ-complexes between Slope and H-magnitude, which suggests there is a tie between space weathering and asteroid size. One possible explanation (Binzel, 2002), is that the smaller an asteroid is, the less time it is able to exist in the main belt before being broken apart through collisions into objects that are so small we cannot detect them. This shorter lifetime results in less space weathering being seen on smaller objects than on larger objects.

Running-box average plots and least-squares line fitting analysis done in this study revealed the interesting finding of a PC2' dependence on Phase Angle in the SQ-complexes, and especially in the Q-complex. This dependence was significant at the 5% level, which implies there is a true correlation between the two variables. The effect of Phase Angle on PC2' seen in the study was not large enough to jeopardize the taxonomic assignments made by Bus and Binzel, but instead may partly explain why the Sq-type asteroids are seen to have such a wide range of PC2' values.

The PC2' dependence on Phase Angle suggests that for higher phase angles, multiple reflections at the asteroid surface have to occur before light is reflected towards the Earth. Multiple scattering implies that the surface of the asteroid must be rough, with particle sizes much larger than the wavelength of light. Future studies with a larger data set may provide more insights into the PC2' and Phase Angle relationship found in this study.

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