Asteroid age distributions determined by space weathering and collisional evolution models

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ABSTRACT

We provide evidence of consistency between the dynamical evolution of main belt asteroids and their color evolution due to space weathering. The dynamical age of an asteroid’s surface (Bottke et al. 2005; Nesvorný et al. 2005) is the time since its last catastrophic disruption event which is a function of the object’s diameter. The age of an S-complex asteroid’s surface may also be determined from its color using a space weathering model (e.g. Willman et al. 2010; Jedicke et al. 2004; Willman et al. 2008; Marchi et al. 2006). We used a sample of 95 S-complex asteroids from SMASS and obtained their absolute magnitudes and u, g, r, i, z filter magnitudes from SDSS. The absolute magnitudes yield a size-derived age distribution. The u, g, r, i, z filter magnitudes lead to the principal component color which yields a color-derived age distribution by inverting our color-age relationship, an enhanced version of the ‘dual τ’ space weathering model of Willman et al. (2010).

We fit the size-age distribution to the enhanced dual τ model and found characteristic weathering and gardening times of $\tau_w = 2050 \pm 80$ Myr and $\tau_g = 4400^{+700}_{-500}$ Myr respectively. The fit also suggests an initial principal component color of $-0.05 \pm 0.01$ for fresh asteroid surface with a maximum possible change of the probable color due to weathering of $\Delta PC = 1.34 \pm 0.04$. Our predicted color of fresh asteroid surface matches the color of fresh ordinary chondritic surface of $PC_1 = 0.17 \pm 0.39$.

Keywords: Asteroids, dynamics, surfaces
1. Introduction

During the twentieth century the number of known main belt (MB) asteroids jumped from less than 500 to nearly 20,000. The mushrooming inventory led to the discovery of asteroid families (Hirayama 1918) and the discovery of the colors of the main spectral types (Chapman et al. 1975). This was followed late in the century by the creation of an extensive database of colors by the Sloan Digital Sky Survey (SDSS (Abazajian et al. 2009)), making possible high statistics color population studies of asteroids. However, an outstanding missing element in the understanding of asteroid evolution was a timeline — at least until dynamical methods were developed for estimating family age (e.g. Marzari et al. 1995; Vokrouhlický et al. 2006a,b; Nesvorný et al. 2002). The combination of family ages and colors based on remote observations led to the Jedické et al. (2004) relationship between an asteroid surface’s color and its age. We will define the ‘color’ of an asteroid as a linear combination of filter magnitudes. It is correlated with spectral slope (Willman et al. 2008). An independent measure of an asteroid’s age depends on its size — the surface of a large asteroid remains intact longer than a small one because it suffers fewer catastrophic disruptions.

The age of an asteroid family can be determined by several dynamical methods, including family size frequency distribution (SFD) modeling, global MB SFD modeling, modeling of family spreading via thermal forces, and backward numerical integration of orbits (Nesvorný et al. 2005). A combination of these methods provides age estimates for about 20 S- and C- complex families.

Until recently, few families were known to be younger than ten Myr. Prior to 2006 there were only two such S-complex families, Karin and Iannini, but in that year Nesvorný et al. (2006a) and Nesvorný and Vokrouhlický (2006b) identified four small genetic clusters of asteroids aged < 1 Myr. Two years later Pravec et al. (2009) and Vokrouhlický and Nesvorný (2008) discovered even younger dynamical pairs of asteroids that separated < 500 kyr ago.

The ensemble of all family asteroid ages as determined by orbital dynamical calculations spans four orders of magnitude and is the first factor required to understand the rate of space weathering using the age-color relationship.

The second factor was color. A conundrum for three decades has been the mismatch between the spectra of the most common meteorites (ordinary chondrites) and their most likely source (inner main belt S-complex asteroids). The space weathering hypothesis was postulated (Chapman and Salisbury 1973) as a means of reconciling the bright, relatively blue spectra with deep absorption bands of ordinary chondrites and the dark, red spectra with shallow absorption bands of S-complex asteroids. It proposes that the surface colors of
asteroids of the same mineralogy will change in a systematic way with airless exposure to the space environment.

The rate of color change on S-complex asteroids has been measured only within the last decade, providing models of surface reddening rate and color range (Willman et al. 2010, 2008; Nesvorný et al. 2005; Jedicke et al. 2004). Space weathering may be due to a combination of mechanisms that could include solar protons or heavier ions, electrons, ultraviolet radiation, micrometeorites, and cosmic rays (see e.g. Chapman (2004) and references therein). However here, as in Willman et al. (2010), we are primarily concerned with the phenomenology of space weathering rather than its cause.

Some recent space weathering models have assumed that the amount of unweathered surface will decay exponentially over time (Willman et al. 2010; Jedicke et al. 2004). One would expect this result if the flow of the weathering agent was constant, an approximation that is probably valid over long periods of time. Willman et al. (2010) assume that at the nanometer scale a part of the surface is either unweathered or weathered and that the two states have distinct colors. The physical motivation for this assumption is the metallic iron film deposited on surfaces of nanophase silicate grains under bombardment by pulsed lasers (Sasaki et al. 2001) or ion sputtering (Loeffler et al. 2009).

Even as an asteroid’s surface ages, weathered surface is transformed back to an unweathered state by regolith gardening at an entirely different rate due to micrometeorites, impact ejecta, seismic shaking, electrostatic levitation, etc. With both weathering and gardening in mind Willman et al. (2010) developed their ‘dual τ’ model to describe the changing colors of S-complex asteroids as a function of age, the time since the family was created in a catastrophic collision that generated a fresh surface on all family members. The name ‘dual τ’ captures the usage of independent characteristic times for both space weathering \( \tau_w \) and regolith gardening \( \tau_g \). Their model extended the single \( \tau \) model of Willman et al. (2008) and Jedicke et al. (2004) by including young clusters in the analysis and by explicitly including the physics of regolith gardening. The dual \( \tau \) model yielded exponential characteristic times for weathering and gardening of \( \tau_w = 960 \pm 160 \) Myr and \( \tau_g = 2000 \pm 290 \) Myr respectively.

The dual \( \tau \) weathering time is consistent with four other results. Pieters et al. (2000) used colors of craters dated by radiometry and cosmic ray exposure ages to determine that space weathering on the moon happens within 100-800 Myr. This corresponds to a space weathering time of 600-4800 Myr in the MB assuming the cause is primarily solar in origin and the effect drops off as \( 1/r^2 \).

Similarly, Veverka et al. (1996) found that craters on (243) Ida are bluer than their surrounding background terrain. The craters correspond to freshly exposed and unweathered
regolith while other parts of the asteroid’s surface indicates an age of about 1 Gy (Greenberg et al. 1996). The wide range in diameters (a proxy for crater age) of blueish crater suggests that the space weathering time must be long.

In lab experiments Sasaki et al. (2001) measured a weathering time of 100 Myr at 1 AU based on laser bombardment of olivine samples (equivalent to 600 Myr in the MB) and this result was confirmed by Brunetto et al. (2006).

However, discrepant results include Loeffler et al. (2009) who measured a weathering time of only 0.005 Myr at 1 AU based on He ion bombardment of olivine powder. Brunetto et al. (2006) summarize ion irradiation experiments finding a reddening time scale of order 1 Myr. Vernazza et al. (2009) propose a two-stage process with the first accounting for most of the weathering and occurring in < 1 Myr.

An independent surface age estimate can be determined from an asteroid’s size and its probability of catastrophic disruption e.g. Bottke et al. (2005). Asteroid surfaces are completely reset during catastrophic disruptions by impactors with diameters that are at least a few per cent of the target’s diameter while smaller impactors will only have local surface effects. Thus, the rate of catastrophic disruption of asteroids depends on their size frequency distribution (SFD) — the larger the asteroid the longer it will survive catastrophic disruption. The SFD can be determined with observations for large objects or through simulating MB collisional evolution that is constrained by the observational results e.g. Bottke et al. (2005). The interval between catastrophic disruptions as a function of size can only be determined from simulations.

In this work we use a sample of asteroids with known sizes and colors to fit a color-age distribution to the independent size-age distribution using an ‘enhanced dual $\tau$’ model. There is no a priori reason the two age distributions must match for any combination of parameters. However, we will show that the size-age and color-age methods are consistent and support both our space weathering model and the collisional evolutionary models. Our enhanced dual $\tau$ model will correctly predict the color of fresh ordinary chondritic (OC) material.

2. Data sample

Our goal is to compare independent age distributions determined from the sizes and colors of a sample of asteroids. To isolate the effect of space weathering we use only S-complex asteroids thus reducing the inherent mineralogical variation of the sample but still including OC-like objects as shown by e.g. Gaffey et al. (1993) and Moroz et al. (1996). Thus, we
selected a sample of 97 S-complex asteroids from the Small Main-belt Asteroid Spectroscopic Survey (SMASS) Bus and Binzel (2002) that also have $u, g, r, i, z$ filter magnitudes and absolute magnitudes, $H$, from the Sloan Digital Sky Survey (SDSS) (Ivezić et al. 2002). SMASS provided moderate resolution spectra and definitively identified these asteroids as members of the S-complex. While this sample is smaller than the one in our previous work (Willman et al. 2010) it has the advantage that each member has rigorous type identification instead of simply relying on family membership.

We used the SDSS $u, g, r, i, z$ filter magnitudes to assign a color to each asteroid from which we determined its color-based age (color-age). Following Nesvorný et al. (2005) the principal component color for an SDSS asteroid is

$$PC_1 = 0.396(u-g-1.43) + 0.553(g-r-0.44) + 0.567(g-i-0.55) + 0.465(g-z-0.58).$$ (1)

Willman et al. (2008) showed that $PC_1$ is correlated with spectral slope where increasing $PC_1$ corresponds to redder asteroids. Almost all the sample members have $0.15 < PC_1 < 0.82$ with two outliers near $PC_1 = 1.70$. We exclude the outliers because of their extreme colors leaving 95 sample members. Leaving the 2 objects in the sample has little impact on the final result.

We independently determined the asteroid’s ages from their diameters as derived from their absolute magnitudes. The diameter, $D$, for each asteroid was calculated (Bottke et al. 2005) from its absolute magnitude, $H$, and albedo, $p_v$, where we used an average albedo of $0.215 \pm 0.041$ from another sample of 93 S-complex asteroids from Bowell (2008):

$$D\text{ km} = \frac{1329}{\sqrt{p_v}} 10^{-H/5} = 2863 \times 10^{-H/5}. $$ (2)

### 3. Color-ages from the dual $\tau$ model

Willman et al. (2010) characterized the changing color of an S-complex asteroid’s surface as a function of time with their dual $\tau$ model

$$PC_1(t) = PC_1(0) + \Delta PC_1[1 - U(t, \tau_w, \tau_g)]$$ (3)

where

$$U(t, \tau_w, \tau_g) = \frac{e^{-\left(\frac{1}{\tau_g} + \frac{1}{\tau_w}\right)t} + \frac{\tau_w}{\tau_g}}{1 + \frac{\tau_w}{\tau_g}}.$$ (4)

The four parameters, $PC_1(0)$, $\Delta PC_1$, $\tau_w$, and $\tau_g$ were fit to the asteroids’ colors, $PC_1$, and ages, $t$, using the least squares method. They found $PC_1(0) = 0.37 \pm 0.01$, the color
of unweathered surface, \( \Delta PC_1 = 0.33 \pm 0.06 \), the maximum possible color change, and 
\( \tau_w = 960 \pm 160 \) Myr and \( \tau_g = 2000 \pm 290 \), the characteristic weathering and gardening times respectively.

We can invert eq. 3 to determine an S-complex asteroid’s surface age from its color;

\[
T_c = \frac{-1}{(\frac{1}{\tau_g} + \frac{1}{\tau_w})} \ln \left[ 1 - \left( \frac{PC_1(t) - PC_1(0)}{\Delta PC_1} \right) \left( 1 + \frac{\tau_w}{\tau_g} \right) \right].
\]  

The logarithm in eq. 5 disallows negative arguments that result from color values above the upper limit of 
\( PC_{1,\text{max}} = PC_1(0) + \frac{\Delta PC_1}{1 + \frac{\tau_w}{\tau_g}} \),
and restricts the invertible color range to \([PC_1(0), PC_{1,\text{max}}]\) with a concomitant restriction in the range of predicted surface ages. This is not a mathematical artifact; in the simple analytic model gardening forestalls net weathering at the equilibrium color of \( PC_{1,\text{max}} \) and asteroids can not be younger than freshly exposed surface. This exposes a fundamental problem with the dual \( \tau \) model — fitting a function involves finding the central tendency of the data which leaves outlying points beyond the function range. In our sample of 95 objects about \( \frac{1}{3} \) of the colors exceed the allowed range of the model.

Thus, we developed an enhanced model described in the next section that is based upon a probability density function (PDF) relating color and age. The model retains the advantage of incorporating the demonstrated color-age relationship while avoiding the inversion singularities.

4. Color-ages from the enhanced dual \( \tau \) model

The enhanced dual \( \tau \) model is a PDF given by

\[
z(t, PC_1) = \frac{N}{\sqrt{2\pi}\sigma_c^2} \exp \left[ -\frac{(PC_1 - PC_1(t))^2}{2\sigma_c^2} \right]
\]  

where \( N \) is a normalization constant such that \( \int \int z \, dPC_1 \, dt = 1 \), \( PC_1(t) \) is the dual \( \tau \) model of eqs 3 and 4, and \( PC_1 \) and \( t \) are free parameters. \( PC_1 - PC_1(t) \) is the deviation from the predicted color, \( PC_1(t) \), for a given age.

To aid in interpreting the PDF the left side of Figure 1 provides an example of the enhanced dual \( \tau \) model using a linear time scale — each vertical cross-section at a fixed age, \( t \), is gaussian with its mean at \( PC_1(t) \) and a standard deviation in color of \( \sigma_c \).
Fig. 1.— Top) The enhanced dual $\tau$ model of eq. 7 with $\tau_w = 2050$ Myr, $\tau_g = 4400$ Myr, $PC_1(0) = -0.05$, and $\Delta PC_1 = 1.34$. This set of parameters is explained in §6. Darker regions correspond to higher probability. We use a linear time axis to facilitate the normal interpretation of a pdf with equal areal density signifying equal probability. Bottom) The same function using a logarithmic time scale.

Our choice of $\sigma_c$ was motivated by the dual $\tau$ model that was based on a fit to the average colors of twelve asteroid families. The average rms spread of the families’ colors had a mean of $0.085 \pm 0.017$ (rms) (Willman et al. 2010). Given the small deviation between the asteroid families’ rms spread we used a constant $\sigma_c = 0.085$.

Given an S-complex asteroid’s $PC_1$ the best estimate for its age is the weighted mean
Fig. 2.— (dash dot) The color-age from the inverted dual $\tau$ model (eq. 5) which is undefined outside the dotted lines and further constrained at the (dash dot dot) asymptote by gardening. (dashed) The same function using enhanced dual $\tau$ model parameters and (solid) the weighted mean color-age from eq. 8 that is defined for all colors. The axes are flipped relative to Figure 1 because age is now considered a function of color instead of vice versa.

The color-age

$$< T_c(PC_1) > = \frac{\int_{0}^{t_f} t z(t, PC_1) \, dt}{\int_{0}^{t_f} z(t, PC_1) \, dt} \quad (8)$$

shown in Figure 2. Since $z(t, PC_1)$ is defined for all colors as well as for ages dating back to the beginning of the solar system, $t_f$, this color-age avoids the inversion singularities of the dual $\tau$ model.

However, eq. 8 does not account for the fact that an asteroid $i$’s color includes a
measurement error, $\Delta PC_{1,i}$, that we model as a gaussian PDF:

$$s_i(PC_1) = \frac{1}{\sqrt{2\pi}(\delta PC_{1,i})^2} e^{-\frac{(PC_1-PC_{1,i})^2}{2(\delta PC_{1,i})^2}}. \tag{9}$$

Convolving this PDF with the enhanced dual $\tau$ PDF yields the age dependent color-age PDF

$$T_{c,i}(t) = \frac{\int_{-\infty}^{\infty} z(t, PC_1) s_i(PC_1) dPC_1}{\int_0^{t_f} dt \int_{-\infty}^{\infty} z(t, PC_1) s_i(PC_1) dPC_1}. \tag{10}$$

Eq. 10 is not sensitive to $t_f$. For instance, the difference between using the age of the solar system (4.5 Gyr) and the age of the oldest known asteroid family, Maria, at 3.0 Gyr, results in a negligible shift of the PDF to slightly younger ages.

Summing the color-age PDFs of all the asteroids in our sample yields their combined differential color-age distribution

$$dN_c(t) = \sum_i T_{c,i}(t) \, dt, \tag{11}$$

the upper envelope of the curves shown in Figure 3. The envelope’s maximum is near 1400 Myr but its mean lies near 2050 Myr due to the tail toward older ages. The envelope’s mean is the analog of the weighted mean given in eq. 8 that corresponds to the enhanced dual $\tau$ model parameter $\tau_w$ in Table 1.

5. Age distribution from asteroid sizes

In the previous two sections we developed the enhanced dual $\tau$ model that enabled us to derive an age distribution from a sample of asteroid colors. We now develop an independent age distribution based on asteroid sizes utilizing the fact that large asteroids are resistant to catastrophic disruptions and therefore have older ages than small asteroids. While large asteroids may be rubble piles reaccumulated in the aftermath of previous collisions (e.g. Marzari et al. 1995), the age calculated here is the time since the most recent catastrophic collision that last reset the asteroid’s surface age.

A common technique in simulating the MB’s collisional evolution is to numerically model the asteroids’ collisional cascade. The simulations begin with an assumed initial SFD with asteroids distributed across different diameter bins that then evolve as a function of time accounting for the asteroids’ specific energy as a function of diameter. An asteroid that suffers a collision disappears from its bin and its fragments appear in their respective size
The average age, $\overline{T}$, of asteroids in a diameter bin is half the average collisional lifetime in the bin, $\tau$, which in turn is the mean time before destruction by catastrophic collision. The average collisional lifetime is the product of the occupancy, $N$, and disruption interval, $t_{\text{dis}}$, in the bin:

$$\overline{T} = \frac{\tau}{2} = \frac{N}{2} t_{\text{dis}}.$$  (12)

We obtained the quantities from the results of a simulation by Bottke et al. (2005) as shown
We used power law fits to $N$ and $t_{\text{dis}}$ to calculate the average age as a function of diameter. We restricted the fit to the diameter range of 1-46 kilometers relevant to our 95 asteroids and find that $N \sim 5 \times 10^5 (D/km)^{-2.07} dD/km$ where $dD$ is the diameter bin width, and $t_{\text{dis}} \sim 1000 (D/km)^{2.97}$. Combining eq. 2 with the last three equations results in a size-derived age

$$T_s(\text{yr}) = 3.23 \times 10^{(11.0 - 0.18H)}$$

(13)

where we use the observed absolute magnitude as a proxy for diameter.

The size-age distribution for our sample using eq. 13 is shown in Figure 5.
6. Results and discussion

In the previous two sections we described how to obtain an age distribution based on asteroid color (color-age) as well as a diameter dependent age distribution (size-age) derived from collisional evolution models. In this section we fit the color-age PDF to the size-age distribution. The fit yields the enhanced dual \( \tau \) parameters given in Table 1 and the function shown in Figure 5.

![Figure 5](image_url)

Fig. 5.— (solid) The size-age distribution from eq. 13 for our sample of 95 S-complex asteroids that are in both SDSS and SMASS, (dotted) the fit binned color-age distribution that yields the enhanced dual \( \tau \) model, and (dashed) the resulting differential color-age distribution from eq. 11.

Our enhanced dual \( \tau \) model is substantially different in functional form, data sample, and derived parameters from the earlier single and dual \( \tau \) models. The difference in functional form is particularly relevant to the value and interpretation of the color parameters, \( PC_1(0) \) and \( \Delta PC_1 \). The broadened range of the color parameters reflect the fact that the PDF of
Table 1: The space weathering model parameters for S-complex asteroids derived from average family colors (single $\tau$, Willman et al. (2008); dual $\tau$, Willman et al. (2010)) or from fitting the color-age PDF to the size-age distribution (enhanced dual $\tau$).

| Model           | $PC_1(0)$  | $\Delta PC_1$ | $\tau_w$  | $\tau_g$   |
|-----------------|------------|---------------|------------|-------------|
| Single $\tau$   | 0.31 ± 0.04 | 0.31 ± 0.07   | 570 ± 220  | na          |
| Dual $\tau$     | 0.37 ± 0.01 | 0.33 ± 0.06   | 960 ± 160  | 2000 ± 290  |
| Enhanced dual $\tau$ | −0.05 ± 0.01 | 1.34 ± 0.04  | 2050 ± 80  | 4400$^{+700}_{-500}$ |

The enhanced dual $\tau$ model is not constrained in color and its inversion allows ages to be assigned to asteroids of any color.

We expect $PC_1(0)$, the most probable value for the initial color of unweathered S-complex asteroids, to be bluer than the majority of objects in the complex. It should also match the color of freshly exposed surfaces of ordinary chondrite meteorites in the laboratory. The average color of 329 ordinary chondrite spectra\(^1\) from Cloutis (1994) is $PC_1 = 0.17 ± 0.39(rms)$ in agreement with our new value of $PC_1(0) = −0.05 ± 0.01$. The large RMS on the mean meteorite color may be due to differences in the meteorite’s particle sizes and mineralogical subtypes. Thus it is difficult to make a meaningful comparison between the meteorite colors and remotely sensed colors of asteroids with unknown surface regolith structure.

Our long space weathering time of about 2000 Myr is surprisingly different than Vernazza et al. (2009)’s result of less than 1 Myr. We are unsure how to reconcile this three order of magnitude difference. Their result relies on several corrections to the colors of asteroid families and it is unclear what age was assigned to freshly cut meteorite surfaces. On the other hand, we fit our model to a sample of less than 100 objects where most span the size range of about 1 – 20 km and an age range of about 100 – 3000 Myr yet we predict, to within 0.5 $\sigma$, the colors of meteorites that are orders of magnitude removed in both size and age. However we recognize that the meteorites’ RMS color variation is large.

It is also possible that there are two weathering processes having different time scales.

\(^1\)Of the 418 ordinary chondrites listed in Cloutis (1994) 329 included spectra, had sufficient wavelength coverage, and were not irradiated. We calculated a spectral slope of 0.10 ± 0.46/µm over the SMASS standard wavelength range of 0.44 – 0.92µm and converted it to $PC_1$ using the transformation derived in Willman et al. (2008). Vernazza et al. (2009) calculated a slope of 0.01/µm over a narrower wavelength range that introduces a systematic offset of ~0.07/µm between their slope and this work. Correcting their value with this offset leads to only 0.02/µm difference in our slope measurements.
However, our data sample is not large enough to justify exploring whether different weathering time scales are present. The decade of size range we use would not be sensitive to the short timescales because the objects are too large to have experienced recent catastrophic disruption. Clearly, the resolution of the discrepancy between the long and short weathering times requires further work and insight.

In the absence of gardening $\Delta PC_1$ is the maximum possible change of the most probable color of S-complex asteroid surfaces. Gardening constrains the most probable maximum color from eq. 6 to a lower value of $PC_1(0) + \Delta PC_1/(1 + \tau_w/\tau_g) = 0.91 \pm 0.07$ as illustrated in Figure 2. Figure 1 shows that S-complex asteroids will not reach maximum redness even over the age of the solar system — consistent with our sample having a maximum $PC_1 = 0.82$.

The dual and enhanced dual $\tau$ models give weathering times differing by $\sim 6\sigma$ as shown in Table 1. However, they were derived using independent data sets and different fit techniques. The dual $\tau$ model was fit to color vs. age data while in this work we fit the inverted enhanced dual $\tau$ model to an age distribution determined from sizes. We believe the methodology of the probabilistic enhanced dual $\tau$ model is superior because it avoids the color truncation problem of the dual $\tau$ model, and attribute the large difference in $\tau_w$ between the models to different data sets and small sample size. We expect that in the future larger data samples with good colors along with better collisional evolution models should resolve the discrepancy. The main goal here was to compare the consistency of ages from collisional evolution models and the color inversion method. The agreement of the age distributions in Figure 5 accomplishes our goal.

Willman et al. (2010) showed that the gardening time calculated there (Table 1, dual $\tau$) was $\sim 7\times$ longer than the resurfacing time calculated from impact rates and cratering physics. The enhanced dual $\tau$ model gardening time is yet another $2\times$ longer! The difference in the values is probably due to the same reasons suggested above to account for the difference in weathering times — small sample size and the use of early collisional evolution models to estimate the size-age of the asteroids.

The fidelity of our results to reality depends on the assumptions used in this work. For instance, we have assumed that $\sigma_c$, the color width of the PDF as a function of time, is constant and equal to a specific value determined from the RMS color distribution within families, when it may actually vary with age. With a larger sample size and more accurate colors it may be possible to fit $\sigma_c$ as a function of time.

Probably the largest systematic uncertainty in this work is the assumption that the collisional evolution model is correct as we have fit the color-age to the size-age distribution. Those models depend on several ill-determined inputs including but not limited to 1) the
current MB SFD 2) estimates of the initial SFD after accretion 3) disruption, cratering, and ejecta physics 4) that material strength as embodied in the specific disruption energy, $Q^*(D)$, is independent of mineralogy 5) and that all objects experience the same density and speed of impactors. For instance, the mean semi-major axis of our sample is $2.63 \pm 0.39 (\text{rms}) \pm 0.04 (\text{err})$ AU compared to $2.806 \pm 0.300 (\text{rms}) \pm 0.001 (\text{err})$ AU for the unbiased MB. The difference is because our sample of 95 asteroids came from SMASS that selected bright (and therefore closer on average) asteroids for spectra acquisition and because S-complex asteroids are primarily in the inner MB. The offset between the values is a significant fraction of the width of the MB — the spatial density of asteroids increases with semi-major axis, impact speeds rise, and material strength decreases. Additionally, S-complex asteroids have higher density than C-complex asteroids which will affect their likelihood of disruption. We hope that future collisional evolution models will incorporate more detail to allow a better comparison between space weathering and gardening time estimates.

We also assumed that the space weathering rate is constant. This working assumption is reasonable even if the actual rate oscillates at high frequency relative to our measured rate but could be problematic if there is a secular trend or the rate oscillates slowly. To explore the possibility that the solar induced weathering rate changes with time Rumpf et al. (2009) proposes an expedition to investigate the lunar regolith and plan to test their techniques on Hawaiian lavas.

This work has shown that age distributions from collisional evolution and space weathering models are consistent. Further refinement awaits enhancements in the data sets and mechanisms for both models. While our result based on remote observation of asteroids suggests the weathering time is long it is difficult to reconcile with some lab results. When this remaining discrepancy is resolved we will have solved a four decade long search for the link between ordinary chondrites and S-complex asteroids.

7. Conclusion

We used two independent methods to derive similar age distributions for a sample of 95 S-complex asteroids from SMASS that also have $u, g, r, i, z$ filter magnitudes and absolute magnitudes from SDSS. The first method used absolute magnitudes to calculate diameters that are related to age because large asteroids survive longer than small ones. The second method inverted a probabilistic relationship (the enhanced dual $\tau$ model) between an asteroid’s color and its age. We developed the enhanced dual $\tau$ model to avoid a color truncation problem encountered when inverting the dual $\tau$ model of Willman et al. (2010). We then fit the color-age distribution from the enhanced dual $\tau$ model to the size-age distribution and
showed that there is consistency between the two age determination approaches. This was not inevitable given the entirely independent techniques and suggests we are converging on a self-consistent understanding of both the collisional evolution and space weathering models.

The most probable color for fresh S-complex asteroid surface is $PC_1(0) = -0.05 \pm 0.01$ in agreement with the color of ordinary chondrite meteorites of $PC_1(0) = 0.17 \pm 0.39$. While we are encouraged by the agreement between the two values we realize that it is due to the large color range exhibited by the lab spectra of the meteorites. The wide variation in meteorite colors may be due to differences in particle sizes or subtypes and the absolute difference between our prediction and the color of meteorites may be resolved with a better understanding of asteroid surface regolith.

According to our model the most probable color for S-complex asteroids after infinite time in the absence of gardening is $PC_1(0) + \Delta PC_1 = 1.29 \pm 0.04$. The most probable ultimately attainable color including the effect of gardening is $PC_1 = 0.91 \pm 0.07$. Our model indicates that most asteroids will not achieve this redness over the age of the solar system.

The gardening time of $4400^{+700}_{-500}$ Myr derived here using the enhanced dual $\tau$ model is over twice that found in Willman et al. (2010) that itself was about 7× their calculated resurfacing time. It may be possible to reconcile the difference using modifications to cratering phenomena proposed by Willman et al. (2010).

Based on our small sample of 95 asteroids for which most span a narrow size and age range of about 1 – 20 km and 100 – 3000 Myr respectively we measured a space weathering time of $2050^{+80}_{-130}$ Myr. This is much longer than some results based on particle bombardment experiments that suggest weathering times of less than 1 Myr. We are unable to reconcile the discrepancy with the particle bombardment experiments but it might indicate that protons or He ions are not the primary cause of space weathering in the main belt. We hope that in the future larger data samples combined with improved collisional evolution and space weathering models will solve the problem.

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