A NUMERICAL CHECK OF THE COLLISIONAL RESURFACING SCENARIO

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Abstract. We present a numerical investigation aimed at checking the so-called Collisional Resurfacing scenario (CR) through one important prediction it makes: do the observed inhomogeneities of color indexes within the Kuiper Belt (KB) match inhomogeneities in collision rates and efficiencies? To quantitatively answer this question, a deterministic model has been developed, which estimates the spatial distribution of the relative amount of collisional energy ΣE_{cin} received by objects in the present Kuiper Belt. Several Kuiper Belt configurations have been explored. Results do show some similarities with color-index distributions within the observed belt, in particular a global correlation between high ΣE_{cin} values and high orbital excitations. Nevertheless, for all tested simulations we find other features of the ΣE_{cin} distributions that significantly depart from the spatial distribution of color-index inhomogeneities. The main problems are mainly too weak correlations with inclinations and too large ΣE_{cin} for the plutinos. Whether these contradictions invalidate the whole CR scenario or not remains yet uncertain, since the physical processes at play are still far from being fully understood and the sample of available observational data is still relatively limited. However, it seems nevertheless that the scenario might not hold in its simple present form.

1. Introduction

Contrary to what had been initially expected, a broad range of different colors seems to prevail among Kuiper Belt Objects (KBOs), ranging from neutral (B-V = 0.6) to very red (B-V = 1.2) (Jewitt and Luu, 2001 and references therein). Moreover, these colors do not appear to be randomly distributed within the belt and seem to be correlated to orbital parameters, although there is still some debate on the significance or even the reality of some of these correlations (Jewitt and Luu, 2001). The most widely admitted correlation is the one between bluer color-indexes and high orbital inclinations i (Trujillo and Brown, 2002, Hainaut and Delsanti, 2002, Doressoundiram et al., 2002). A correlation between blue objects and low perihelion q was also found by Doressoundiram et al. (2002), in particular for the classical KBOs (CKBOs). The correlation between blue KBOs and high eccentricities e is less clear, and is in any case weaker than the two previous ones (see discussion in Doressoundiram et al. (2002)).

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Earth, Moon and Planets **92:** 233–241, 2003.

These color-index differences are too strong to be explained by initial physical inhomogeneities (i.e., temperature) within the early Belt (Jewitt and Luu, 2001) and some additional factor must be at play. One of the proposed explanations is the so-called Collisional Resurfacing (hereafter CR) scenario, which we shall focus on in this paper. This scenario is based on the competing effects of space weathering (cosmic and solar cosmic rays, solar radiation, etc. ...) and resurfacing by mutual collisions. In its most simple form, this scenario supposes continuous reddening by space weathering which is counteracted by regular collisional excavation of neutral "fresh" new material. Nevertheless, the physical processes at play are very complex and not fully understood so far, so that CR might significantly depart from this pure-reddening vs. pure-bluing assumption (Gil Hutton, 2002, Moroz, 2003). Thus, it is still difficult to confirm or rule out this scenario on mere physical arguments. However, there might be another and more simple way to check this scenario's validity, which is relatively independent of the complex physical reality of this mechanism. CR should indeed leave a characteristic signature in the way color-indexes are spacially distributed within the Belt. This follows directly from the fact that, while space weathering is supposed to act relatively homogeneously throughout the Belt (or at least the classical belt region), mutual collisional effects, which are obviously linked to collision rates and impacting energies, should more significantly depend on KBOs orbital parameters.

The question is: do we see such a signature in the observed color-index distribution? This question has been recently addressed by Stern (2002), who looked for a correlation between color and the excitation parameter $V_{\mathrm{rms}} = (e^2 + i^2)^{1/2} V_{\mathrm{kep}}$ (where V_{kep} is the keplerian velocity of a given KBO), under the assumption that V_{rms} is a good estimate of a given KBO's mean impact speed. This study gave encouraging results, since such a correlation was indeed found. Nevertheless, such results might be misleading since V_{rms} gives in reality only a very partial information on the collisional behavior of a given body. As an example, an object on a perfectly circular planar orbit ($V_{\mathrm{rms}} = 0$) might be hit by a very excited body, or an object with high e might impact targets far away from its semi-major axis a location (which might have a completely different dynamical environment), or a high V_{rms} object might be located in an empty region with few potential targets, etc. ... The link between collisional activity and orbital parameters is thus a complex one, basically because bodies from very different regions of the belt collisionally interact. We have addressed this problem by using a deterministic numerical model that enabled us to quantitatively estimate the relative spatial distribution of collisional activity within the present Kuiper Belt. These results have then been compared to observational data in order to look for the hypothetical "signature" of the CR scenario, i.e., to check if regions of higher collisional activity do match regions where "bluer" KBOs are located. Some of these results have already been presented elsewhere (Thebault and Doressoundiram, 2003). We would like to highlight here the most significant ones as well as present new calculations exploring different Kuiper Belt configurations.

2. Numerical Procedure

Our model has been described in details in Thébault and Doressoundiram (2003). Let us here briefly recall that we follow the collisional fate of a swarm of 500 test target objects, imbedded in a larger swarm of 4000-to-8000 impactors. For each impact between a target-impactor couple, we compute the impacting kinetic energy E_{cin}. The level of collisional activity of a given target at the end of the run is measured by the value of ΣE_{cin}. In order to provide usable results, our target population, on which the correlations with orbital parameters are estimated, should be as close as possible to the distribution of *observed* KBOs. In Thébault and Doressoundiram (2003) we took a somehow "extended" target swarm (see Table I) in order to get better statistics. Here we have performed additional runs with a target population resembling more the observed belt (Table I), i.e., mainly populating the plutino and CKBO region until 48 AU. The crucial point is of course the *impactor* population, since the collisional activity of a given test-target depends on the whole distribution of all its potential impactors. To get a correct estimate of this potential impactors population we need our impactor disc to be as close as possible to the *real* debiased distribution of objects in the belt. The problem is that this "real" spatial distribution is poorly known and has to be reconstructed from strongly biased observational data. The most problematic features are the inclination distribution and the density of objects beyond the 2:1 resonance at 48 AU. In Thébault and Doressoundiram (2003) we remained careful and considered several possible impactor discs: a sharp cut-off at 48 AU, an extended excited disc, an extended cold disc and an academic SKBO-only swarm. Eccentricities where taken within the $q > 35$ AU stable region and we took an extended flat-top i distribution within 0 and 25 degrees. But the KBO science is a fast evolving one and in the last months the community seems to have agreed on the reality of the cut-off beyond 48 AU (Morbidelli, 2003). Regarding the inclination distribution, a majority of authors now seems to agree on the fact that there is a large population of high i objects, but disagreing on its exact profile. Brown (2001) favors a two-gaussians (peaking at 2 and 18 degrees respectively) multiplied by $\sin i$ distribution. Trujillo et al. (2001)'s best fit is a single gaussian peaking at 20^{-4}_{+6} degrees, but these authors pointed out that the available data could almost equally well be fitted by Brown's bi-gaussian or even by a simple flat-top in the 0 to 30 degrees range. This later flat-top profile was the one considered in Thébault and Doressoundiram (2003), but we present here some additional runs with the Brown and Trujillo distributions (see Table I).

3. Results

The Thébault and Doressoundiram (2003) simulations results have been discussed at length in the corresponding paper. Let us give here a brief overview. One first outcome was that we found global statistical correlations between high-collisional

TABLE I

Initial conditions for the target populations and for different impactor disks considered (in Thébault and Doressoundiram (2003)) and in the present additional runs)

	Semi-major axis (AU)	Eccentricity	Inclination
Target population	$a^{-1}da$	$a(1-e) > 35$	$0 < i < 25°$
(Thébault and Doressoundiram, 2003)	$38 < a < 55$		
Target population (new run)	$a^{-1}da$	$a(1-e) > 35$	$0 < i < 25°$
	$38 < a < 48$		
Impactor disks:			
Outer cutoff	$a^{-1}da$	$a(1-e) > 35$	$0 < i < 25°$
(Thébault and Doressoundiram, 2003)	$38 < a < 48$		flat top
Outer cutoff 1 (new run)	$a^{-1}da$	$a(1-e) > 35$	Trujillo et al., 2001 distribution:
	$38 < a < 48$		gaussian ($i_{1/2} = 20°$)
Outer cutoff 2 (new run)	$a^{-1}da$	$a(1-e) > 35$	Brown, 2001 distribution:
	$38 < a < 48$		bigaussian*sin$i$ ($i_{1/2} = 2.2°$ & $i_{1/2} = 18°$)
Excited outer disc	$a^{-1}da$	$a(1-e) > 35$	$0 < i < 25°$
(Thébault and Doressoundiram, 2003)	$38 < a < 75$		flat top

activity and several parameters, above all $V_{\rm rms}$, e, and q (cf Table II). Such correlations present similarities with the global statistical correlations with color-indexes within the observed belt, in particular the fact that they are significantly "blurred", with for example a large dispersion of $\Sigma E_{\rm cin}$ for a given $V_{\rm rms}$ value (see Fig. 2 of Thébault and Doressoundiram (2003)). This blurring reflects the wide variety of collisional environments for bodies sharing common e, i or $V_{\rm rms}$ values. However, when looking more closely at the results, we did find several features that strongly contradict observational correlations. First of all, there is the high level of collisional activity of the plutinos, which have on average (in the cutoff case) an excess of 90% in $\Sigma E_{\rm cin}$ with respect to the average value for CKBOs (Table II). To the present day, no such tendency towards "bluer" plutinos has been found for observational data. Another problem was that collisional activity was, in our runs, always more clearly correlated to the targets' eccentricities than to their inclinations (Table II). This is in itself a logical result, due mainly to: (1) the "out of plane" effect affecting high i targets. The higher impacting speeds of these objects is compensated by the fact that they spend a larger fraction of their orbit outside the Belt's mid-plane, in a region where less potential impactors are present; and (2) the fact that the Belt has much more structure in e, with in particular the limiting $a(1 - e) > 35$ AU stability condition, than in i. Objects with same e thus tend to be in a similar dynamical environment and share similar collisional fates. However, this "logical" result is the exact opposite of observed correlations with color-indexes, which are clearly correlated to i and weakly (or maybe not at all) to e.

In the new simulations with the Trujillo et al. (2001) and Brown (2001) distributions for the impactor disc, one interesting result is a slight improvement of correlations between $\Sigma E_{\rm cin}$ and targets' inclination. This is due to the decrease of the "out of plane" effect, that previously limited collision rates of *targets* with high i, because *impactors* are now much less concentrated towards the belt's mid-plane. As a consequence, i and e correlations are now at equivalent levels (Table II), which is an improvement with respect to the Thébault and Doressoundiram (2003) simulations. Nevertheless, we are still far from the strong i vs. low e correlations for observed color-indexes (Table II). Furthermore, this improvement has been made at the cost of a new problem: a global decrease of all other correlations with orbital parameters. This is in itself a logical result: since impactors have here much higher inclinations, they have (on average) higher excitations than the targets they hit. This tends to diminish the contribution of the targets' excitations to the impacting kinetic energies and thus the correlation between these two parameters. We are thus left with correlations values that are far from the levels measured for color-indexes within the "real" belt ; especially when considering the fact that we have not taken into account the effect of impactors from the scattered disc. These objects' high excitations should indeed tend to weaken even more all correlations with targets' orbital parameters (see discussion in Thébault and Doressoundiram (2003)).

TABLE II

Correlations obtained, for CKBO targets, between $\Sigma E_{\rm cin}$ and orbital parameters, for different runs considered in Thébault and Doressoundiram (2003) and in the present paper. As a comparison, we also give the correlations between color-index and orbital parameters for all published CKBOs as given in Doressoundiram et al. (2002). Correlations are given using Spearman's rank correlation coefficient $r_{\rm corr}$. They range from -1 (ideal anticorrelation) to 1 (ideal correlation), with 0 standing for completely uncorrelated data. The values under brackets give $P(r > r_{\rm corr})$, the probability for obtaining a higher or equivalent coefficient from uncorrelated data. We also give, for all simulations, the ratio between the average impacting kinetic energy received by plutinos and by CKBOs

Impactor disc considered	Eccentricity	Inclination	Perihelion	$V_{\rm rms}$	$\frac{<\Sigma E_{\rm cin}>_{plutinos}}{<\Sigma E_{\rm cin}>_{CKBOs}}$
48 AU cutoff Thébault and Doressoundiram (2003)	$0.33(3.10^{-12})$	$0.12(0.05)$	$-0.48(4.10^{-25})$	$0.36(4.10^{-13})$	1.9
48 AU cutoff (Trujilo et al. *i* distribution)	$0.17(3.10^{-3})$	$0.19(10^{-3})$	$-0.24(6.10^{-6})$	$0.22(4.10^{-5})$	1.35
48 AU cutoff (Brown, 2001 *i* distribution)	$0.20(2.10^{-4})$	$0.18(3.10^{-3})$	$-0.25(2.10^{-6})$	$0.23(2.10^{-5})$	1.48
Excited outer disc Thébault and Doressoundiram (2003)	$0.27(8.10^{-8})$	$0.14(0.015)$	$-0.28(5.10^{-8})$	$0.32(9.10^{-10})$	1.40
Correlations with color index *for all published CKBOs* Doressoundiram et al. (2002)	$0.21(0.15)$	$0.53(8.10^{-5})$	$-0.25(0.08)$	$0.49(4.10^{-3})$	–

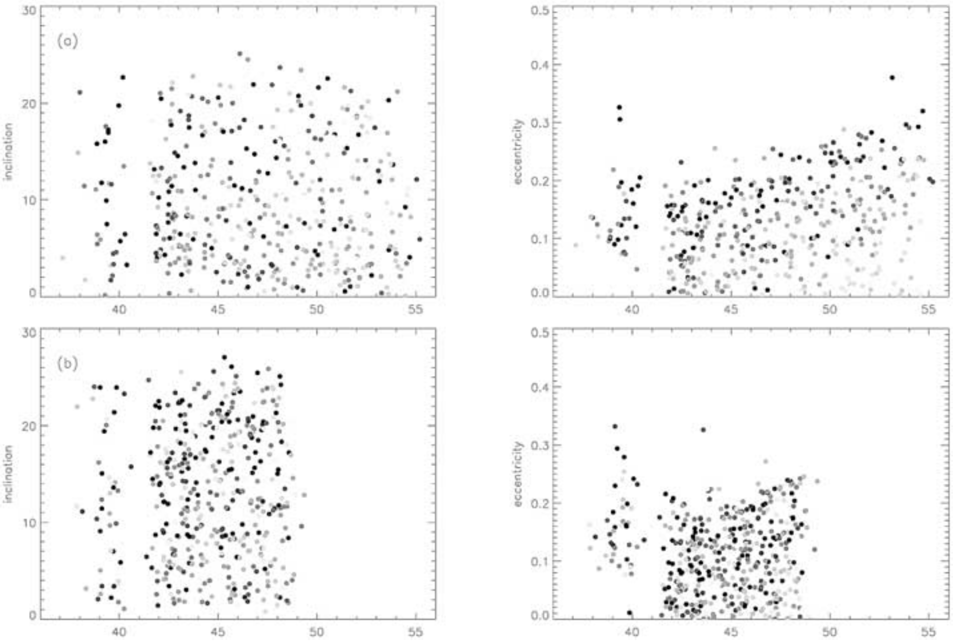

Figure 1. (i, a) and (e, a) plots of the *relative* ΣE_{cin} distribution within the target disc for (a) the 48 cutoff impactor disc considered in Thébault and Doressoundiram (2003) and (b) the 48 cutoff disc considered in our newest run (see Table I for details). For each graph, ΣE_{cin} levels have been arbitrary rescaled on a black and white scale, with black standing for the highest ΣE_{cin} values.

Moreover, the problem of the plutinos' high level of collisional activity, though less pronounced, is still present (cf. last column of Table II).

4. Discussion and Conclusions

None of the impactor disc profiles that have been tested turned out with a satisfying ΣE_{cin}relative distribution: inhomogeneities in the spatial distribution of collisional activity do only partially match observed inhomogeneities in color-index distribution. This is a serious problem for the CR scenario since it casts a shadow on one important prediction this scenario makes. Of course, it should be possible to construct an ad-hoc impactor disc profile yielding more "satisfying" relative ΣE_{cin} distributions, but such an artificial disc would probably strongly depart from any "reasonable" KBO distribution profile.

One could argue that these problems arise because of the simplicity of our model. We do not believe this to be the case, mainly because our simple model is adapted to the study of the *simple* problem we intend to address, i.e., where are the regions of higher collisional activity located in the Belt, and how well are they related to regions with "bluer" KBOs? In this respect, we believe our approach to be a step forward from the basic search for correlations between colors and V_{rms} which had been done until now.

Of course, one mechanism has been deliberately left out of our study, i.e., the competing space weathering process. Our main assumption was that this mechanism should act rather homogeneously throughout the classical belt and that spatial inhomogeneities in the color-index distribution should preferentially arise from collisional activity. Let us recall that the robustness of this assumption is that its validity is independent from the extreme complexity of the physical effect of space weathering on TNO surfaces: what matters here is if there are *spatial inhomogeneities* in space weathering effects within the belt or not. In a very recent study Cooper (2003) stressed that there actually might be such inhomogeneities in the outer solar system. Nevertheless, it is far from being certain if such inhomogeneities might be significant within a relatively narrow region such as the classical belt. Should nevertheless this be the case, then there might be a marginal possibility that space weathering *alone* could be responsible for the observed color-index distribution.

It is thus too early to reach any definitive conclusions about the CR scenario. One should also keep in mind that the amount of reliable observational data on color-index is still relatively limited and the present values of the correlations with i, e or q are far from being definitive. Nevertheless, it seems that the CR scenario cannot hold in its present simple form and that it has to be seriously reinvestigated.

Another and more radical possibility would be to renounce the CR scenario in favor of an alternative explanation, the so-called 2 populations model. In its present version, this model states that differences in colors could be due to the presence of two different populations of objects: a dynamically cold ($i < 4°$) population formed at its present location and a dynamically excited ($i > 4°$) population formed closer to the Sun (in the present Jupiter to Uranus region) which has been ejected by violent events (Tegler and Romanishin, 2000, Levison and Stern, 2001). Nevertheless, this scenario raises also some problems. Firstly, there is still some debate about the statistical significance of a division at $i = 4°$ (Malhotra, 2003, personal communication), the question of the debiased KB inclination distribution being still a difficult topic. Another problematic topic is the dynamical process generating the "hot" KBO population. Gomes (2003) has numerically investigated this question and proposed an attractive dynamical scenario. Nevertheless, there are still problems to solve, like the fact that it seems difficult to get a segregation in inclinations without getting a similar (or even stronger) segregation in eccentricities between the hot and cold populations (whereas no such segregation has been found in observational data yet).

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