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Modeling the Color Distribution of Kuiper Belt Objects

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Abstract

Observations show that 100-km-class KBOs can be divided into two color groups, hereafter red (R) and very red (VR), reflecting a difference in their surface composition. This is thought to imply that KBOs formed over a relatively wide range of radial distance, r. The cold classicals (CCs) at $42 < r < 47$ au are mostly VR and known Neptune Trojans at $r \simeq 30$ au are predominantly R. Intriguingly, however, the dynamically hot KBOs show a mix of R and VR colors and no correlation of color with r. Here we propose that these observations can be best understood if R objects formed at $r < r^*$ and VR objects at $r > r^*$, with $35 < r^* < 40$ au. To explain the distribution of colors in the dynamically hot populations, we conducted new migration/instability simulations where the Kuiper belt is populated from a source planetesimal disk extending from below r^* to above r^* (as required to obtain a mix of colors). We used these new simulations to determine how the existing color data constrain the radial disk profile and r^*. The results help us to identify possible causes of the color bimodality.

1. Background

The vast majority of KBOs are too faint for spectroscopic observations, but their surface composition can be studied with broadband photometry. Photometric observations indicate that the color distribution of KBOs is bimodal with red (R; defined as $g - i < 1.2$; Wong & Brown 2017) and very red (VR; $g - i > 1.2$) classes. Known Neptune Trojans at $r \simeq 30$ au are predominantly R (Jewitt 2018) and most classified CCs with semimajor axes $42 < a < 47$ au are VR. This has been taken as an evidence that colors have something to do with the radial distance at which different objects formed. Confusing matters, however, the dynamically hot populations with $30 < a < 50$ au show a mix of R and VR colors, and there does not appear to be any obvious correlation of colors with r.

Brown et al. (2011) proposed that the early surface compositions of KBOs were set by volatile evaporation after the objects formed. A strong gradient in surface composition, coupled with UV irradiation and particle impacts, then presumably led to the surface colors that we see today. For example, the sublimation line of (pure) ammonia, NH_3, is near 34 au (Brown et al. 2011). Objects formed at the current location of CCs may therefore uniquely retain NH_3, which has been shown to affect irradiation chemistry and could plausibly lead to the VR colors of these objects. But how to interpret the R colors of Neptune Trojans and the bimodal distribution of colors in the hot population?

Neptune Trojans were presumably trapped as co-orbitals during Neptune's migration. Their inferred formation location is $r \simeq$ 25-30 au. The uniformly R colors of Neptune Trojans would thus be hard to understand if the R to VR transition is related the sublimation line of the hydrogen sulfide ice (H_2S, $r \simeq$ 15-20 au; Wong & Brown 2017). Instead, the R colors of Neptune Trojans seem to imply that the transition occurred farther out, probably beyond ∼30 au. This reasoning leads to an impasse, however, because our current dynamical models suggest that the dynamically hot KBOs were implanted onto their current orbits from the massive planetesimal disk at $r < 30$ au (e.g., Nesvorný & Vokrouhlický 2016). Their colors should thus be uniformly R, just like Neptune Trojans, but they are not.

2. Color Hypothesis

A plausible solution of this problem, which we investigated here, is to examine the possibility that the hot populations in the present-day Kuiper belt are a mix of bodies implanted from the massive disk below 30 au (source of R) and the low-mass disk extension beyond 30 au (source of VR). On one hand, the surface density of planetesimals must have significantly dropped at $r > 30$ au for Neptune to stop at 30 au. The outer disk extension thus represents a smaller source reservoir than the massive disk below 30 au. On the other hand, the chances to evolve from 30-40 au onto a dynamically hot orbit in the Kuiper belt are better. It is

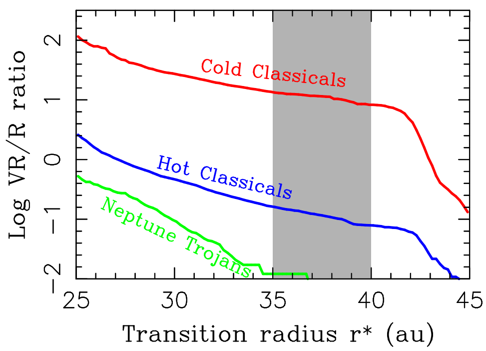

Figure 1: A test of the suggested color hypothesis. Here we assumed that the surface density of the original planetesimal disk had an exponential profile and performed a full scale simulation along the lines described in Nesvorný & Vokrouhlický (2016) to determine the VR/R ratio. The lines indicate the VR/R ratio as a function of the transition radius r^* for different populations: CCs (red), HCs (blue) and Neptune Trojans (green). The case with $r^* \simeq$ 35-40 au (shaded area) best matches the color distribution inferred from observations.

thus plausible that a good share of hot KBOs come from the 30-40 au region (Figure 1).

Note, in addition, that the suggested color transition at $r^* > 30$ au can explain why the VR objects among hot KBOs have smaller orbital inclinations than the R objects (e.g., Marsset et al. 2019 and the references therein), because the orbital excitation from Neptune is expected to weaken for orbits starting beyond 30 au (Figure 2). In contrast, no such correlation would be expected if both the R and VR objects started below 30 au, where Neptune's gravitational effects are uniformly strong.

If some of the R objects can be pushed out from $r < r^*$ into the CC population, this could explain the red CC binaries reported in Fraser et al. (2017). The new color hypothesis is also consistent with the uniformly R colors of irregular satellites (e.g., Graykowski & Jewitt 2018). The suggested transition from the R to VR colors at $r^* > 30$ au can be a consequence of the sublimation-driven surface depletion in some organic molecules, such as NH_3 (Brown et al. 2011).

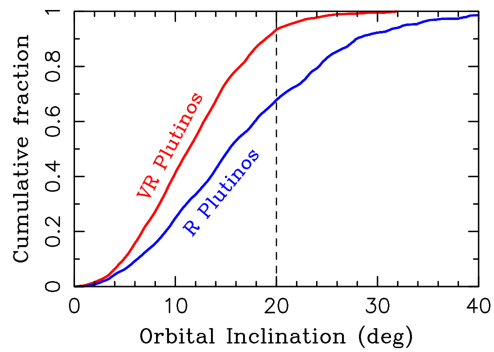

Figure 2: The simulated inclination distribution of Plutinos in the 3:2 resonance with Neptune. Here we assumed that $r^* = 37$ au and separated objects into those that started below 37 au (assumed R, blue line) and above 37 au (assumed VR, red line). In this case, about 95% of VR Plutinos have $i < 20°$ and about 30% of R Plutinos have $i > 20°$. This result provides a good match to the observed color-inclination correlation (e.g., Marsset et al. 2018).

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