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The size-distribution of scattered disk TNOs from that of JFCs between 0.2 and 15 km effective radius

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ABSTRACT

We investigate the differential size–frequency distribution (SFD) of Jupiter Family Comets (JFCs) in order to determine whether they are primordial accreted objects or collisional fragments as suggested by current models of the evolution of Trans-Neptunian Objects (TNOs). We develop a list of effective radii and their uncertainties for 161 active JFCs from published sources and compute the observed differential size–frequency distribution using a Probability Index technique. The radii range from 0.2 to 15.4 km and average 1.9 km. The peak of the distribution is near 1.0 km. This is then corrected for the effects of observational selection using a model published earlier by Meech et al. (Meech, K.J., Hainaut, O.R., Marsden, B.G. [2004]. Icarus 170, 463–491). We estimate that the total number of active JFCs between 0.2 and 15.4 km is approximately 2300 indicating that our current sample of the of active JFC population is far from complete. The active JFC size–frequency distribution, over the range from 0.6 to 10 km where it is best defined, is found to be closer to an exponential distribution in character than a power-law. We then develop a statistical model, based on the assumption of a steady state, for converting the distribution of active JFCs to the SFD of the source population among the TNOs. The model includes the effects of devolatization (that produces a large sub-class of defunct nuclei) and surficial mass-loss. Comparison with available TNO observations shows that to simultaneously attain continuity with the data on objects in the hot TNO population (Fuentes et al. [2010]. Astrophys. J. 722, 1290–1304), satisfy constraints on the number of TNOs set by the occultation detections of Schlichting et al. (Schlichting, H.E. et al. [2012]. Astrophys. J. 761, 150), and to remain within upper limits set by the Taiwanese–American Occultation Survey (TAOS; Zhang et al. [2013]. Astron. J. 146, ID 14, 10pp.) the total JFC population must contain a large fraction of small defunct nuclei. The effective power-law index of the inferred TNO differential SFD between 1 and 10 km is -4.5 ± 0.5 indicating a population in this range that is not in fully relaxed collisional equilibrium. We conclude that the cometary nuclei so far visited by spacecraft and many JFCs are primordial accreted objects relatively unaffected by collisional evolution. We find a turndown in the slope of the predicted TNO cumulative distribution near 1 km radius rather than near 10 km that is seen in many TNO evolutionary calculations. This may or may not represent the onset of a collisional cascade.

1. Introduction and basic assumptions

Are small objects (0.1–10 km in radius) in the scattered disk TNO (Trans-Neptunian Object) population, which are the putative source population of comet nuclei observed today as Jupiter Family Comets (JFCs), representative samples of primitive accreted objects much as first outlined by Weidenschilling (1997), or are they more representative of collisional fragments as suggested by the calculations of Davis and Farinella (1997), or even collisionally processed aggregates (primitive rubble piles) as discussed by Weissman et al. (2004)?

Farinella and Davis (1996) addressed a version of this question and their modeling indicates that TNOs in the relevant size range would be part of a cascade of collisional fragments that would display a power-law size–frequency distribution (SFD) with a differential index near −3.5. Recent modeling (see Kenyon et al. (2008) for a review) continues to support this view as well as giving a more detailed idea of what the shape of the cumulative SFD in this size range might look like. The most recent modeling (Schlichting et al., 2013) continues to show how important the effects of collisions can be on the evolving SFD. In parallel with this modeling there has been a concerted effort by several groups of Earth-based observers to determine the SFD of JFCs and measure the slope of its cumulative SFD (most recently Fernández et al., 2013; Weiler et al., 2011; Snodgrass et al., 2011; Tancredi et al., 2006; Meech et al.,

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2004). Their results for the cumulative power-law index, -2.01 ± 0.21; -1.9 ± 0.2; -1.92 ± 0.20 ($r > 1.25$ km), -2.7 ± 0.3 (obtained from the absolute nuclear magnitude range of $\sim$14–16 mag), and -1.45 ± 0.05 ($1 < r < 10$ km) respectively, are sensitive to the size range employed and, except for the result of Tancredi et al. (2006), are all some way away from the cumulative size-distribution slope of -2.5 expected for a collisional cascade in equilibrium (Dohnanyi, 1969), but not necessarily the predicted cumulative slope of -2.04 in a steady-state population of nuclei with no material strength by O'Brian and Greenberg (2003). It is of interest to note that the three most recent studies give effectively identical results while the outlier at -2.7 is probably due to the short baseline in effective radius (2.1–5.3 km).

Now, however, we have certain aspects of spacecraft observations of JFCs that question the collisional scenario outlined above. Brownlee et al. (2004) and Weaver (2004) were the first to suggest, on the basis of high-resolution Stardust Mission images, that the rounded shape of the nucleus of 81P/Wild2 did not seem consistent with a collisional fragment and that it was probably not a rubble pile. They considered that their results presented a "challenge" to the collisionally processed aggregate paradigm. Subsequent discovery of deep-seated, global-scale, layers on 9P/Tempel 1 in the data from the Deep Impact and Stardust-Next missions (Thomas et al., 2007, 2013a,b) and their interpretation as primordial layers by Belton et al. (2007) also appears to be in conflict with "models of fragmentation and rubble pile building." Similarly, there is the lack of any convincing or, at least, non-controversial, evidence of wide-spread impact cratering on the surfaces of the observed nuclei as predicted by Durda and Stern (2000). While the globally distributed pits seen on 81P/Wild 2 (Brownlee et al., 2004) have been interpreted as impact craters (Basilevsky and Keller, 2007), they are, in our opinion, more likely to be sublimational or erosional pits caused by internal or outburst activity (Belton, 2010). Similarly, the widespread distribution of pits seen on 9P/Tempel 1 are more reasonably explained by comet outburst activity than by impact (Belton et al., 2013).

It therefore appears that there may be a serious conflict between expectations for comet nuclei based on modeling of collisional evolution in the Kuiper belt and what high-resolution geophysical studies of individual nuclei tell us. A resolution may possibly come from two directions. First, many of the Kuiper belt evolution calculations depend on a fragmentation model that was developed for understanding the evolution of rocky asteroids that suffer hypersonic collisions. As far as we are aware a competent model of *comet fragmentation at sub-sonic speeds* does not yet exist and it may be that the 'rocky' model of fragmentation is not appropriate for TNOs. The collisional cascade SFD of real comet nuclei may have a different character, *i.e.,* shape and slope, from that which is currently predicted. Secondly, there are other uncertainties in this kind of modeling that involve the coupling of dynamical and collisional evolution. These are, in our opinion, well exposed in the work of Charnoz and Morbidelli (2003, 2007) and could lead to a different assessment of the effects of collisional evolution. On the other hand, it surely can be argued that since the data from spacecraft missions is relatively new, current results and interpretations are not assured. So there is ample opportunity for new interpretations to be devised for what is observed.

Our approach to resolving these problems is twofold: First, establish the differential SFD of scattered-disk TNOs (SDOs) in a size (effective radius) range relevant to the mission-observed comet nuclei, *i.e.*, JFCs, and compare with the results of models of collisional erosion. We do this by an extrapolation from the observed SFD of JFCs taking into account the effects of observational selection, devolatization, and mass-loss. Second, establish a model of comet impact fragmentation for low to moderate relative speeds that is based on the many astronomical observations of the phenomenon, and, for higher speeds, the results of the hypersonic Deep Impact experiment (Schultz et al., 2007; Richardson et al., 2007). The first Item is the focus of this paper; the second investigation is reserved for a future paper that is currently in preparation.

To proceed it is necessary to make some basic assumptions: First, we will accept the result that a dynamical connection currently exists between the SDOs and JFCs as originally worked out by Levison and Duncan (1997) and Duncan et al. (2004) and adopt the timescales for the various dynamical processes that were established in their work. Secondly, we will assume that both the SDOs and JFC size frequency distributions (averaged over a timescale of $\sim 10^4$ year [see below]) are currently in a *steady-state*, specifically that they are independent of time and that the dynamical processes involved in the transfer of an SDO to a JFC nucleus are independent of size. There is no observational evidence to support the steady-state assumption that we are aware of, however, the evolutionary calculations of Volk (2013) and Brasser and Morbidelli (2013) indicate that, while systematic changes in the scattered disk are expected to occur, their effects are quite small over timescales of 10^4–10^8 year (see Volk (2013) for a detailed discussion of the steady state hypothesis and the possible effect of an episodic fluctuation). Finally, we will also assume that (i) the density distribution in the interior of comet nuclei is homogeneous (Belton et al., 1991): (ii) that the individual shapes of comet nuclei do not affect the calculations, (iii) that their size can be represented by an *effective radius*, *r*, and, (iv) that the effects of mass-loss on size while a comet nucleus is in its Centaur stage are negligible (for a review of activity in these objects see Jewitt, 2009).

In Section 2 we establish the statistical relationship between the JFC and SDO differential SFDs. In Section 3 we provide background on the observed SDOs and JFC size frequency distribution and establish the observed JFC size frequency distribution that we will use in this work. This section also discusses the relevant orbital properties of the JFC sample that we use. In Section 4 we adjust the observed SFD for observational selection effects based on a model suggested by Meech et al. (2004). In Section 5 we compute the SFD for scattered disk TNOs by simultaneously constraining its parameters with three independent observations of the hot TNO population. Finally, in Section 6, we provide a discussion of our results in terms of the question posed above.

2. The relationship between the JFC and SDs size–frequency distributions

To be clear, we first define what is included in the sub-set of comets that we call JFCs. Following Duncan et al. (2004) we group comets according to their Tisserand parameter, *T* (defined with respect to Jupiter), and orbital inclination, *i* and define JFCs as those comets that lie between the following limits:

$$2.4 \leqslant T \leqslant 3.1 \quad \text{and } 0 \leqslant i \leqslant 31^\circ \tag{1}$$

The usual definition of JFCs is $2 < T < 3$ (Duncan et al., 2004) and our adjustment of these limits is to include comets like 2P/Encke and a few others that have a Tisserand parameter slightly greater than 3 and to definitely exclude Oort type comets. Our chosen range ensures that the comets we employ likely originated as SDOs and have subsequently been introduced into their current orbits by dynamical interaction with Jupiter (see the review by Duncan et al., 2004). As discussed in the following section, the limits in Eq. (1) also reflect the population of JFCs for which a size determination is available and there are 161 in our list (Table 1). In what follows we also include the possibility of a sub-class of defunct nuclei in the JFC population. "Defunct" is a term used by Jewitt (2004) to describe both dead, *i.e.*, exhausted of volatiles, and dormant comets, *i.e.*, comets