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Characterizing the original ejection velocity field of the Koronis family

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ABSTRACT

An asteroid family forms as a result of a collision between an impactor and a parent body. The fragments with ejection speeds higher than the escape velocity from the parent body can escape its gravitational pull. The cloud of escaping debris can be identified by the proximity of orbits in proper element, or frequency, domains. Obtaining estimates of the original ejection speed can provide valuable constraints on the physical processes occurring during collision, and used to calibrate impact simulations. Unfortunately, proper elements of asteroids families are modified by gravitational and non-gravitational effects, such as resonant dynamics, encounters with massive bodies, and the Yarkovsky effect, such that information on the original ejection speeds is often lost, especially for older, more evolved families.

It has been recently suggested that the distribution in proper inclination of the Koronis family may have not been significantly perturbed by local dynamics, and that information on the component of the ejection velocity that is perpendicular to the orbital plane (v_W), may still be available, at least in part. In this work we estimate the magnitude of the original ejection velocity speeds of Koronis members using the observed distribution in proper eccentricity and inclination, and accounting for the spread caused by dynamical effects. Our results show that (i) the spread in the original ejection speeds is, to within a 15% error, inversely proportional to the fragment size, and (ii) the minimum ejection velocity is of the order of 50 m/s, with larger values possible depending on the orbital configuration at the break-up.

1. Introduction

Asteroid families are the outcome of high-velocity collisions between asteroids. If the fragments of collisions have speeds exceeding the escape velocity from the parent body, they may be ejected and form a swarm around the main body (or, in case of a catastrophic collision, around the family barycenter). Since the terminal ejection speeds are only a fraction of the orbital speed of most main belt bodies, the fragments are not ejected far and may be identified by the fact that they form clusters in the domain of proper elements (a, e, $\sin(i)$) (or proper frequencies ($n, g, g+s$) (see Knežević and Milani, 2000 for a description of the methods used to obtain proper elements and frequencies), with a, e and i being the asteroids proper semi-major axis, eccentricity, and inclination, and n, g, s being the proper mean-motion, frequency of precession of the longitudes of pericenter, and of the node, respectively (Bendjoya and Zappalà, 2002; Carruba and Michtchenko, 2007).

Theoretically, ejection speeds of asteroid family members could be estimated from the distribution in proper elements (a, e, $\sin(i)$) using Gauss' equations (Zappalà et al., 1996), provided that both the true anomaly and the argument of perihelion of the family parent body are known (or estimated). In practice, several gravitational and non-gravitational effects, such as resonant dynamics (Morbidelli and Nesvorný, 1999), close encounters with massive asteroids (Carruba et al., 2003), and the Yarkovsky effect (Bottke et al., 2001) can change proper elements of asteroid families, so that information on the original ejection speeds is sometimes lost, especially for older, more dynamically evolved groups.

Recently, however, Carruba and Nesvorný (2015), based on arguments on the current shape of the distribution in $\sin(i)$ of the Koronis family, suggested that information on the component of the ejection velocity that is perpendicular to the orbital plane (v_W) may still be available for this family, at least in part.[1] In this work we extend the analysis of the previous paper, and try for the first

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[1] Information on the original ejection velocity field could be in principle also obtainable from very young families proper e and i distributions, such as for instance the Datura and Lorre clusters. Here however we focus our attention on a

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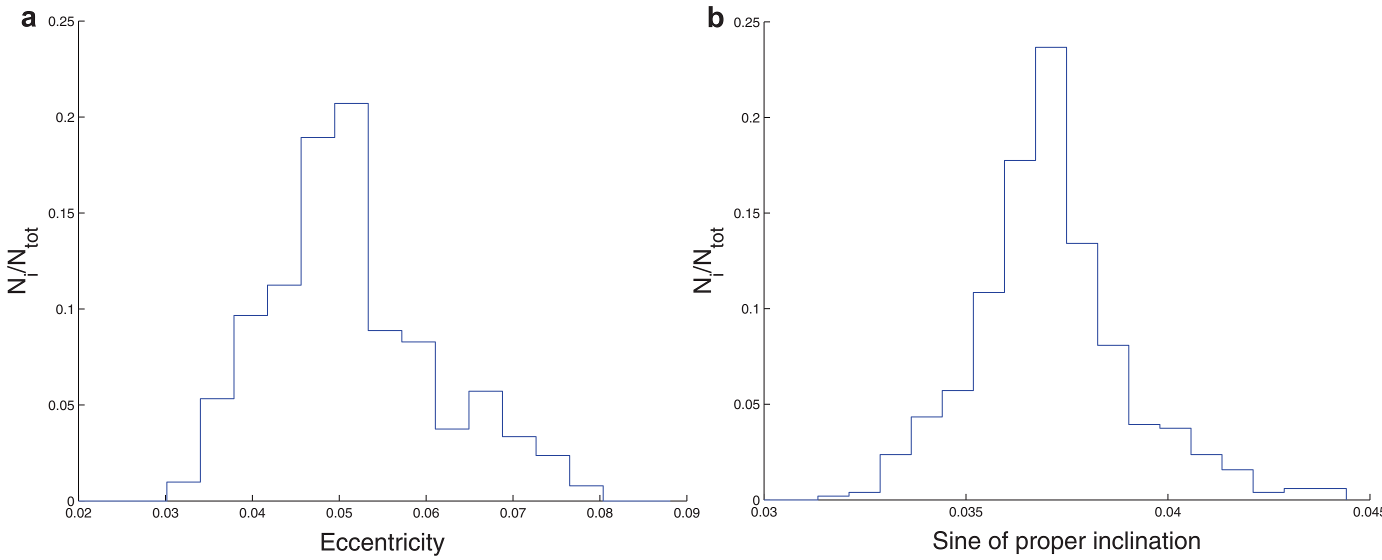

Fig. 1. Panel A: histograms of the frequency distribution in proper eccentricity e for a reduced Koronis family with proper semi-major axis $a < 2.88$ AU, for objects with $2 < D < 4$ km (D_3 population). Panel B: similar histograms, but for the distribution in proper sine of inclination $\sin(i)$.

time to obtain estimates of the original spread of the ejection velocity field for the Koronis group, based on the *eccentricity and inclination* distributions, rather than on the semi-major axis one, as previously attempted (Carruba et al., 2015b). By performing long-term simulations of fictitious Koronis members, we were able to evaluate the effect that dynamics may have had on the inclination distribution, and to estimate what the original distribution should have been, so allowing us to obtain a value of the spread in ejection speeds.

This paper is so divided: in Section 2 we identify the Koronis family and its halo, and we verify what is the current dispersion of the family in proper e and $\sin(i)$. In Section 3 we study the effect that the local dynamics may have had on the orbital evolution of Koronis family members, and determine to which extent the original distribution in e and $\sin(i)$ have been preserved. In Section 4 we estimate what was the original dispersion of the Koronis family in proper inclination, determine how the spread in original inclination depended on the family members sizes, and estimate what was the magnitude of the family original ejection velocity field. Finally, in Section 5 we present our conclusions.

2. Family identification

The Koronis family is located in a relatively dynamically quiet region, where, with the exception of the $3\nu_6 - 2\nu_5 = g + 2g_5 - 3g_6$ secular resonance, a pericenter resonance that mostly modifies asteroid eccentricities, no other major mean-motion or secular resonance exists (Bottke et al., 2001; Carruba et al., 2013; Nesvorný et al., 2015). The long-term dynamics of the Koronis family should therefore had had a minor influence in the spreading in proper i of members of the family, as we will also further investigate later on in this paper. Despite being a relatively old family (2.65 Gyr at most if one use standard values for the parameters describing the Yarkovsky force; Brož et al., 2013; see Carruba et al., 2015b and references therein for more detail on this age estimate), the current dispersion in proper i of Koronis family members could therefore still contain traces of information on the original ejection speeds (Cellino et al., 2009; 2004).

To investigate this hypothesis, we first obtained an estimate of the current family members. We used data published in Nesvorný et al. (2015) for the Koronis family using the Hierarchical Clustering Method (Zappalà et al., 1990), and a velocity cutoff of 45 m/s in the (a, e, $\sin(i)$) domain (see Table 2 in Nesvorný et al., 2015 for further details). Since there are two subfamilies inside the Koronis group, the Karin cluster (Nesvorný et al., 2002; 2006) and the Koronis 2 family (Molnar and Haegert, 2009), we eliminated these two subgroups from the list of Koronis members. This left us with a sample of 5163 objects, out of the original 5949 members of the whole Koronis and subfamilies sample.

To eliminate possible interlopers, we used the classification method of DeMeo and Carry (2013) that employs Sloan Digital Sky Survey-Moving Object Catalog data, fourth release (SDSS-MOC4 hereafter, Ivezić et al. (2001) to compute *gri* slope and $z' - i'$ colors, and data from the three major photometric/spectroscopic surveys: ECAS, Eight-Color Asteroid Analysis, (Tholen, 1989; Zellner et al., 1985), SMASS, Small Main Belt Spectroscopic Survey (Bus and Binzel, 2002a; 2002b; Xu et al., 1995), and S3OS2, Small Solar System Objects Spectroscopic Survey (Lazzaro et al., 2004). We obtained 896 observations in the SDSS-MOC4 catalog, and taxonomical information for 507 individual asteroids in the revised Koronis family (i.e., the Koronis family, less the two sub-families of Karin and Koronis 2). We found 3 C-type, 8 D-type, 29 X-type, 109 L-type, 259 S-type, 98 K-type, and 1 A-type objects, respectively.

Our results confirm the analysis of Binzel et al. (1993) and Carruba et al. (2013, 2015b) the Koronis family is an S-complex group, with a small percentage (40 objects, 7.9% of the available sample) of C-complex interlopers. This is further confirmed by the values of geometric albedos p_V from the WISE mission (Masiero et al., 2012) for local asteroids. Out of the 507 asteroids with taxonomical information, 284 have data in the WISE dataset. Only one object (25285 1998 WB7) has a value of p_V less than 0.1, normally associated with C-complex asteroids, and could be considered an albedo interloper.

After eliminating three more objects outside the Yarkovsky isolines of the Koronis family (see Nesvorný et al., 2015, Section 4), we were left with a sample of 5118 asteroids. Fig. 1, panel A, displays a histogram of the frequency distribution in proper e for a reduced Koronis family with proper $a < 2.88$ AU (to avoid including asteroids that crossed the $g + 2g_5 - 3g_6$ secular resonance and other mean-motion resonances, see next section for a more

relatively old family, to check whatever information may still available for more evolved groups.