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Recent collisional jet from a primitive asteroid

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ABSTRACT

In this paper we show an example of a young asteroid cluster located in a dynamically stable region, which was produced by partial disruption of a primitive body about 30 km in size. We estimate its age to be only 1.9 ± 0.3 Myr; thus, its post-impact evolution should have been very limited. The large difference in size between the largest object and the other cluster members means that this was a cratering event. The parent body had a large orbital inclination and was subject to collisions with typical impact speeds higher by a factor of 2 than in the most common situations encountered in the main belt. For the first time, we have at our disposal the observable outcome of a very recent event to study high-speed collisions involving primitive asteroids, providing very useful constraints to numerical simulations of these events and to laboratory experiments.

Key words: methods: numerical – celestial mechanics – minor planets, asteroids: general.

1 INTRODUCTION

The asteroid population, being steadily subject to a process of collisional evolution (Davis et al. 1989; Bottke et al. 2005; Asphaug 2009; Morbidelli et al. 2009), provides excellent possibilities to study the physics of collisional events. Asteroid families, which are believed to originate from catastrophic disruption of single parent bodies (Zappalà et al. 2002), are, almost one century since the pioneering work by Hirayama (1918), still an attractive and challenging subject. They provide a key to our understanding of the collisional history of the main asteroid belt (Bottke et al. 2005; Cellino, Dell'Oro & Tedesco 2009), outcomes of disruption events over a size range inaccessible to laboratory experiments (Michel, Benz & Richardson 2003; Durda et al. 2007; Asphaug 2010), clues on the mineralogical structure of their parent bodies (Cellino et al. 2002), the role of space weathering effects (Nesvorný et al. 2005; Vernazza et al. 2009) and to many other subjects.

So far, ejecta from a few tens of large-scale collisions have been discovered across the main asteroid belt (e.g. Zappalà et al. 1995; Mothé-Diniz, Roig & Carvano 2005; Nesvorný et al. 2005). In terms of their estimated ages, most families identified so far are fairly old and have had enough time to evolve significantly since the epoch of their formation as a consequence of (i) chaotic diffusion (Nesvorný et al. 2002a; Novaković, Tsiganis & Knežević 2010b), (ii) semimajor axis drift due to the Yarkovsky effect (Farinella & Vokrouhlicky 1999; Bottke et al. 2001), (iii) secondary collisions (Marzari, Farinella & Davis 1999; Bottke et al. 2005), (iv) non-destructive collisions (Dell'Oro & Cellino 2007) and/or (v) diffusion due to close encounters with massive asteroids (Carruba et al. 2003; Novaković, Tsiganis & Knežević 2010c; Delisle & Laskar 2012).

In this respect, little altered recently born families may provide more direct information about the physics of break-up events. Evidence of recent collisions in the asteroid belt has been reported in the last decade and our knowledge about young asteroid families has been increased significantly (Nesvorný et al. 2002b; Nesvorny, Vokrouhlicky & Bottke 2006a; Nesvorný & Vokrouhlický 2006). Most of these groups are formed by asteroids belonging to the *S* taxonomic class. There are, however, several important differences among the *S*- and *C*-type asteroids. The objects belonging to former class are thought to have experienced some thermal evolution since the time of their formation, and it is, for example, known that space weathering processes are different for these two classes of objects (e.g. Gaffey 2010). Also, numerical simulations show that the outcomes of collisional events are dependent on the internal structure of the parent body (Jutzi et al. 2009). Because of these reasons, it is necessary to also identify young *C*-class families in dynamically stable regions, as a few such groups are already known, but none of these is well suited to extract reliable enough information. Two *C*-type families, namely Veritas and Theobalda, about 8.3 and 6.7 Myr old, respectively, are located in a dynamically unstable region (Nesvorný et al. 2003; Novaković 2010a). Thus, despite their young ages, these families evolved significantly since post-impact situation. Most of the asteroids belonging to the Beagle family (Nesvorný et al. 2008), which is probably less than 10 Myr old,

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are located in a dynamically relatively stable region. However, this group is embedded in the large Themis family making a distinction between the real members of the group and background objects very difficult. Finally, the youngest known group that might be formed by *C*-type asteroids is the Emilkowalski cluster, which is only 220 ± 30 kyr old (Nesvorný & Vokrouhlický 2006). However, it seems to be rather an *X*- than *C*-type group because albedos of its members are much higher than that expected for *C*-type objects. For example, the geometric albedo of the asteroid (14627) Emilkowalski is 0.2013 ± 0.0170 (Masiero et al. 2011).

Thus, it is of extreme importance to identify young families, which belong to the most primitive *C* class, that do not suffer from the above-mentioned problems. We have found the first example of this kind to be the Lorre cluster, recently discovered by Novaković, Cellino & Knežević (2011). According to existing colour data, its largest member, (5438) Lorre, is a primitive carbonaceous *C*-class asteroid, which may contain organic materials. Moreover, the members of this cluster are located in a dynamically stable region and very tightly packed in the space of proper orbital elements (Knežević & Milani 2003), suggesting a likely young age. Therefore, its post-impact evolution should have been very limited. This makes it a very promising candidate for different possible studies. Two crucial prerequisites for these studies are an accurate identification of its members and a reliable estimation of its age. These are the questions we address here.

2 LORRE CLUSTER

2.1 Membership

A dynamical criterion for family membership is based on distances among the objects in the space of proper orbital elements: semimajor axis (a_p), eccentricity (e_p) and inclination (i_p). Usually, for this purpose the hierarchical clustering method (HCM) and 'standard' metric (d) are used (Zappalà et al. 1990, 1994). This metric is defined as

$$d = na_p\sqrt{\frac{5}{4}\left(\frac{\delta a_p}{a_p}\right)^2 + 2(\delta e_p)^2 + 2(\delta \sin(i_p))^2}, \quad (1)$$

where na_p is the heliocentric velocity of an asteroid on a circular orbit having the semimajor axis a_p. $\delta a_p = a_{p_1} - a_{p_2}$, $\delta e_p = e_{p_1} - e_{p_2}$ and $\delta \sin(i_p) = \sin(i_{p_1}) - \sin(i_{p_2})$, where the indices 1 and 2 denote the two bodies under consideration. The HCM connects all objects whose mutual distances (expressed in metres per second) are below a threshold value (d_c).

Following the method described in Knežević & Milani (2000), we calculated synthetic proper elements for 148 asteroids located in a region somewhat wider than that occupied by the cluster. This region covers the following ranges in the osculating orbital elements: $2.738 < a < 2.758$ au, $0.13 < e < 0.39$ and $23° < i < 31°$. The number of asteroids includes numbered, multi- and single-opposition objects,[1] found in the recent version of catalogues of osculating elements retrieved from the AstDys web page.[2] Then, we applied the HCM to this set of proper elements and analysed the number of dynamically linked objects identified at different mutual distances (Fig. 1). In particular, this was done by changing d_c from 10 to 200 m s^{-1} at discrete steps of 10 m s^{-1}. At the lowest tested value of $d_c = 10$ m s^{-1}, the HCM links 14 asteroids with Lorre, while the number of members raises to 19 for 20 m s^{-1}. The number of dynamically associated members remains a constant until 80 m s^{-1}, when one body, the asteroid 2006 AX$_{67}$, is added. Later on, no additional body is linked to the cluster, even for the largest used value of $d_c = 200$ m s^{-1}.

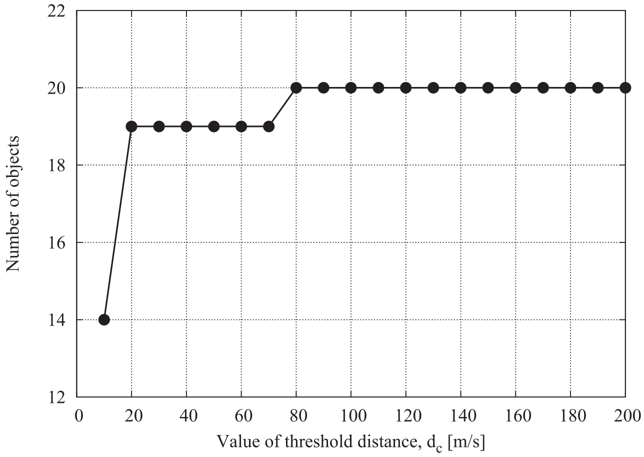

Figure 1. Number of asteroids associated with the Lorre cluster as a function of the cut-off distance d_c. Unusually tightly packed members and sharp distinction of the cluster from background population are two main characteristics.

From these results, we can draw three basic conclusions: (i) the cluster is extremely compact and very well separated from the background population; (ii) the nominal membership of the cluster is best characterized at $d_c = 20$ m s^{-1}; (iii) the asteroid connected with the group at 80 m s^{-1} is likely a close background object. Thus, the Lorre cluster has 19 currently known members (Table 1). These asteroids are very tightly packed with mutual distances significantly smaller than in the cases of typical families in the main asteroid belt.

2.2 Dynamics

The orbits of the asteroids belonging to the Lorre cluster are characterized by the moderate eccentricities ($e_p \approx 0.26$) and high inclinations ($i_p \approx 28°$), but the region occupied by these asteroids is not under the influence of any of the strong mean motion or secular resonances. Thus, despite their orbital characteristics, these asteroids are mostly stable. Still, there are a few mean motion resonances (MMRs), present in the region, whose influence should not be neglected. The most powerful is a three-body[3] MMR 3J−1S−1A located at 2.752 au. Somewhat less significant but still relevant are another two three-body MMRs, namely 1J+4S−1A and 4J+3S−2A (see Fig. 2). Finally, 13J/5A two-body MMR, among Jupiter and asteroid, is present in the region as well.

To better understand the strength of these resonances and their possible influence on the dynamical stability, we have determined Lyapunov times (T_{lyap}) for all members of the Lorre cluster. This was done according to the method proposed by Milani & Nobili

[1] Although the orbits of single-opposition objects are less reliably known, we also used them in order to find as many cluster members as possible.

[2] Asteroids Dynamic Site: http://hamilton.dm.unipi.it/astdys2/

[3] Three-body MMRs are commensurabilities between the mean motions of Jupiter, Saturn and asteroid (Nesvorný & Morbidelli 1998). They are characterized by the relation $m_J\dot{\lambda}_J + m_S\dot{\lambda}_S + m\dot{\lambda} \sim 0$, where $\dot{\lambda}_J$, $\dot{\lambda}_S$ and $\dot{\lambda}$ denote mean motions of Jupiter, Saturn and asteroid, respectively, while m_J, m_S and m are integers.

Table 1. Proper orbital elements of the asteroids belonging to the Lorre cluster. In columns are given: semimajor axis (a_p), eccentricity (e_p), sine of inclination ($\sin(i_p)$), mean motion (n), frequency of the longitude of perihelion (g) and frequency of the longitude of node (s).

Asteroid	a_p (au)	e_p	$\sin(i_p)$	n (degree yr^{-1})	g (arcsec yr^{-1})	s (arcsec yr^{-1})
5438	2.747 32	0.262 90	0.472 30	79.0466	9.4486	−49.7809
208099	2.746 94	0.263 14	0.472 41	79.0630	9.4207	−49.7557
2001 RF_{42}	2.744 27	0.263 21	0.471 76	79.1781	9.5380	−49.7308
2001 XF_{167}	2.747 18	0.263 14	0.472 53	79.0532	9.3965	−49.7490
2003 BW_5	2.747 96	0.262 94	0.471 98	79.0210	9.4916	−49.8129
2003 YY_{120}	2.746 71	0.263 42	0.472 12	79.0732	9.4846	−49.8060
2005 YD_{18}	2.747 88	0.263 13	0.472 46	79.0204	9.4144	−49.7840
2006 AL_{16}	2.746 36	0.263 42	0.472 11	79.0883	9.4880	−49.7946
2006 RM_{98}	2.742 63	0.262 76	0.472 01	79.2495	9.4847	−49.6157
2007 BJ_{62}	2.746 26	0.263 38	0.472 04	79.0927	9.4968	−49.7919
2008 AD_{104}	2.747 22	0.263 08	0.472 40	79.0511	9.4276	−49.7716
2010 CG_{176}	2.745 36	0.262 92	0.471 95	79.1313	9.4935	−49.7350
2011 FQ_{151}	2.745 21	0.262 99	0.471 96	79.1377	9.4915	−49.7297
2010 AX_{32}	2.746 68	0.263 82	0.472 27	79.0744	9.4695	−49.8253
2006 VZ_{122}	2.747 83	0.263 42	0.472 39	79.0216	9.4505	−49.8372
2008 BB_{10}	2.746 31	0.263 48	0.472 20	79.0899	9.4758	−49.7979
2008 DE_8	2.744 90	0.263 18	0.471 93	79.1514	9.5111	−49.7482
2010 EW_{42}	2.745 44	0.263 33	0.471 98	79.1277	9.4987	−49.7634
2010 EJ_{81}	2.742 33	0.263 44	0.472 10	79.2627	9.4890	−49.6575

(1992) and within the framework of several different dynamical models.

As for most of the purposes, in this part of the main asteroid belt, the dynamical model with four major planets (from Jupiter to Neptune) is accurate enough, we first used this model to estimate Lyapunov times. The obtained values of T_{lyap} are in most cases longer than 100 kyr. A few exceptions include objects located around $a_p = 2.7478$ au, which are probably trapped inside the 4J+3S−2A resonance. However, even Lyapunov times of these objects are not shorter than about 30 kyr (Table 2).

When the dynamical model with seven planets, from Venus to Neptune, is used, the estimated Lyapunov times are notably shorter (Table 2), meaning that this model should be used for asteroids located in the region of the Lorre cluster. The reasons for the important difference among the results obtained with four and seven planets are relatively large orbital eccentricities and inclinations of these objects. Still, according to this result, most of the Lorre cluster members are reasonably stable, with the only one possible exception, asteroid 2003 BW_5.

Recently, Laskar et al. (2011) showed that close encounters with massive asteroids may induce chaos in their motion and in the motion of other asteroids. To check whether or not this is the case for Lorre cluster members, we have also calculated Lyapunov times using dynamical models that include some of the most massive asteroids, Ceres, Pallas and Vesta.[4]

Our result generally confirms the one obtained by Laskar et al. (2011). Lyapunov times become, on average, shorter when the massive asteroids are included in the dynamical model. There are, however, a few asteroids whose motion seem to be more stable in this case, and their values of T_{lyap} are longer than those obtained in the model with seven planets only. An illustrative example is the only possible unstable object among the currently known members of the cluster, the asteroid 2003 BW_5. Its estimated T_{lyap} is only 7 kyr in the dynamical model with seven planets, but rises to 22 kyr when Ceres is added to the dynamical model.[5] Thus, although the influence of the massive asteroids on the motion of asteroids belonging to the Lorre cluster is undoubtedly confirmed, its resulting effect may vary from case to case.

The conclusion that we can draw from derived values of Lyapunov times is that the orbits of the Lorre cluster members are neither perfectly stable nor strongly chaotic.

In terms of a possible post-impact dynamical evolution of the cluster, even weak chaos may be important. Hence, to explore this possibility and to assess a jet-like shape of the cluster, we checked the stability of the proper eccentricity and inclination of asteroids belonging to the Lorre cluster. Using the numerical integrations of cluster members performed in the dynamical model that includes seven planets (from Venus to Neptune) and three most massive asteroids (Ceres, Pallas and Vesta), we estimated the average evolution rates of eccentricity and sine of inclinations to be 1×10^{-4} and 5×10^{-5} Myr^{-1}, respectively. These are slow changes that do not seem to be able to significantly change the overall structure of the cluster. Actually, as we found the Lorre cluster to be only about 1.9 Myr old (see Section 2.3), over its lifetime the expected changes in eccentricity and sine of inclination are only about 2×10^{-4} and 1×10^{-4}, respectively. By comparing these values with the scales of the y-axis in Fig. 2, we concluded that dynamical evolution is negligible.

Looking at Fig. 2, it can be easily realized that the distribution of the Lorre cluster members is highly asymmetric with respect to the

[4] For this purpose, the masses of Ceres, Vesta and Pallas are set to 4.757, 1.300 and 1.010 × 10^{-10} $M_\odot$, respectively (Kuzmanoski, Apostolovska & Novaković 2010; Baer, Chesley & Matson 2011). These masses are results of the latest calculations performed by means of the improved methodology. A preliminary estimation of Vesta's mass provided by the Dawn mission (http://dawn.jpl.nasa.gov/mission/) perfectly matches the results from these two papers for this object. Due to these reasons, we chose to use these values, despite being slightly smaller than those used by Laskar et al. (2011).

[5] This is not a surprise because an estimation of Lyapunov times, even for moderately chaotic orbits, is probabilistic, and thus not highly reliable and should be interpreted with care (Knežević & Ninković 2005).

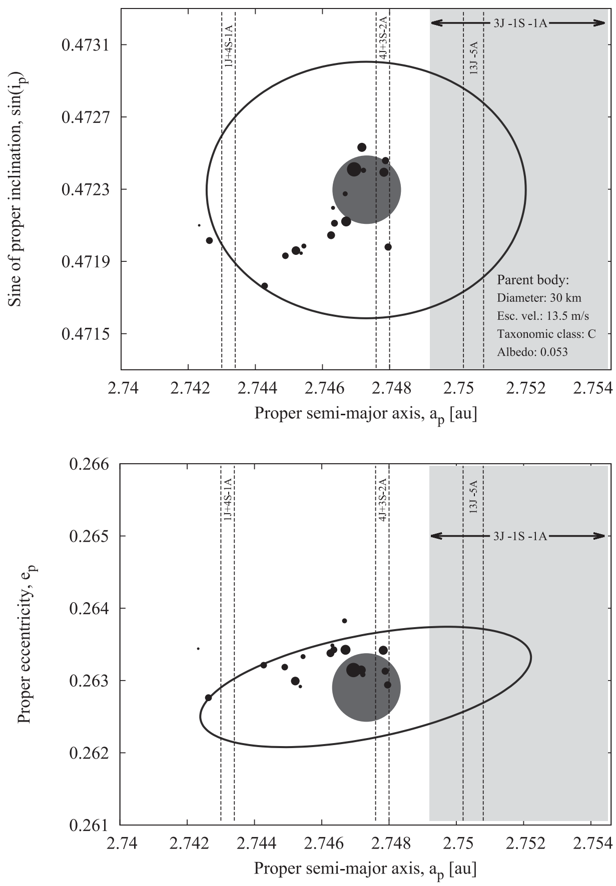

Figure 2. The Lorre cluster in the space of proper elements. The size of each symbol is proportional to the diameter of the body. The superimposed ellipses represent equivelocity curves, computed according to the Gaussian equations (Nesvorný & Vokrouhlický 2006). These ellipses are obtained assuming a velocity change $\Delta v = 15$ m s^{-1}, an argument of perihelion $\omega = 90°$ and a true anomaly $f = 90°$. The ellipses are shown to illustrate the distribution of the fragments in the case of an isotropic ejection field; however, it is easy to see that the ejection velocity field (EVF) of the Lorre cluster was highly asymmetric, a nice example of what one should expect to be the outcome of a cratering event (Vokrouhlický & Nesvorný 2011). The locations of the relevant MMRs are denoted with the vertical dashed lines, except in the case of the 3J−1S−1A resonance that is marked with the grey-shaded region. In the top panel, basic information about parent body is also given.

largest member, the asteroid (5438) Lorre. To understand the reasons for this, we extend our dynamical analysis to the region surrounding the cluster. The dynamical instability starts to increase for values of the semimajor axis larger than 2.748 au. The inner border of the powerful 3J−1S−1A MMR is found at about 2.749 au. However, using numerical integrations of 100 massless test particles, we have verified that this instability cannot explain the absence of cluster members in the 2.748–2.754 au range (see Fig. 2). Although, over a time-scale of 2 Myr, many particles interact with the 3J−1S−1A resonance, they still remain close enough to be recognized by the HCM.

Available evidence suggests, therefore, that the observed asymmetry of the family is mostly a consequence of the original EVF of the fragments, rather than dynamical post-impact evolution. Thus, this cluster still keeps memory of the original EVF, a useful input to study impact physics.

2.3 Age

The most accurate method known so far to estimate the age of a young asteroid family is to integrate the orbits of its members backwards in time and to identify the epoch of their convergence (Nesvorný et al. 2002b, 2003). However, this method can be applied only to the objects on stable orbits. As we showed in Section 2.2 that the orbits of the Lorre cluster members are not perfectly stable, an application of the backward integration method (BIM) is not so straightforward. To overcome this problem, we turn to a statistical approach based on the BIM (Nesvorný & Vokrouhlický 2006; Vokrouhlický & Nesvorný 2011). Instead of orbits of nominal members, we used a number of cloned, statistically equivalent, orbits. In this way, we were able to characterize the age of the Lorre cluster in a statistical sense.

More in particular, we took into account the current orbital uncertainties of the nominal orbits and different possible evolutions of the orbital semimajor axes due to the Yarkovsky effect. For each nominal member of the cluster, except for the asteroid (5438) Lorre, we produced a set of 10 orbital clones. These clones are drawn from the 3σ interval of their formal uncertainties[6] listed in Table 3, assuming the Gaussian distribution. Then, for each of the orbit clones, we generated 10 different 'yarko' clones uniformly distributed over the interval stretching from zero to the maximum expected drift due to the Yarkovsky force (Bottke et al. 2001). The maximum drift in the proper semimajor axis due to the Yarkovsky force $(\mathrm{d}a/\mathrm{d}t)_{\max}$ for each object is obtained assuming thermal parameters appropriate for *C*-type asteroids (Brož & Vokrouhlický 2008). In this way, a total of 100 statistically equivalent clones were assigned to each member. Clones are not used for the asteroid (5438) Lorre itself because on one hand its orbit is very well determined, while on the other hand it is large enough (see Table 4) that the Yarkovsky effect on its orbit can be safely neglected.

The orbits of all clones were numerically integrated backwards in time for 10 Myr using the ORBIT9 software. These integrations were performed within the framework of a dynamical model that includes seven planets, from Venus to Neptune, as perturbing bodies and also accounts for the Yarkovsky effect.[7] To account for the indirect effect of Mercury, its mass is added to the mass of the Sun and the barycentric correction is applied to the initial conditions.

The age of the cluster was estimated by randomly selecting one clone for each member and determining the age for that particular combination of clones as the minimum of the function (Vokrouhlický & Nesvorný 2011):

$$\Delta V = na\sqrt{(\sin(i)\Delta\Omega)^2 + 0.5(e\Delta\varpi)^2}, \qquad (2)$$

where $na \approx 18\,\mathrm{km\,s^{-1}}$ is the mean orbital speed of the asteroids in the cluster, and $\Delta\Omega$ and $\Delta\varpi$ are the dispersions of the longitudes of node and perihelion, respectively.

The obtained results are shown in Fig. 3. The age of the Lorre cluster turns out to be 1.9 ± 0.3 Myr. The estimated error comes mainly from the assumed orbital uncertainties of single-opposition asteroids. Nevertheless, the result is robust and undoubtedly confirms that the Lorre cluster is very recent.

[6] For single-opposition objects we assumed the following values of orbital uncertainties for all of them: $\sigma_a = 2.0 \times 10^{-5}$ au, $\sigma_e = 3.0 \times 10^{-5}$, $\sigma_i = 1.°0 \times 10^{-4}$, $\sigma_\Omega = 2.°0 \times 10^{-4}$, $\sigma_\omega = 3.°5 \times 10^{-4}$ and $\sigma_M = 5.°0 \times 10^{-3}$.

[7] For simplicity, the Yarkovsky effect is included in the model as a constant secular drift (inwards or outwards) of the semimajor axis. This approximation seems appropriate for our purpose to characterize the age of the Lorre cluster in a statistical sense.

Table 2. Lyapunov times of Lorre cluster members derived using different dynamical models.

Asteroid	Four planets	Seven planets	Seven planets + Ceres	Seven planets + Ceres and Vesta	Seven planets + Ceres, Pallas and Vesta
5438	107.6	41.7	35.0	27.2	26.0
208099	128.1	75.4	50.6	32.5	30.7
2001 RF_{42}	290.7	57.7	36.0	29.0	16.1
2001 XF_{167}	82.1	48.2	31.4	35.1	30.6
2003 BW_5	41.2	6.7	21.8	7.9	20.5
2003 YY_{120}	534.8	203.3	39.9	30.0	32.7
2005 YD_{18}	32.5	38.9	29.3	25.1	20.9
2006 AL_{16}	304.0	162.1	41.5	35.8	31.4
2006 RM_{98}	226.2	22.1	14.0	19.2	19.7
2007 BJ_{62}	289.1	219.3	39.7	34.9	35.1
2008 AD_{104}	125.6	41.6	37.8	28.6	26.0
2010 CG_{176}	7142.9	75.1	37.4	36.9	23.0
2011 FQ_{151}	505.5	115.1	34.4	27.1	24.7
2010 AX_{32}	1960.0	198.4	40.9	35.2	31.0
2006 VZ_{122}	35.4	31.8	27.5	25.1	11.5
2008 BB_{10}	552.9	202.0	43.6	35.6	29.7
2008 DE_8	4000.5	83.8	37.6	35.3	31.3
2010 EW_{42}	2381.0	76.0	44.6	33.7	28.8
2010 EJ_{81}	746.6	97.9	42.3	34.2	34.1

Table 3. The osculating orbital elements along with their formal uncertainties of Lorre cluster members at epoch 560 00.0 MJD as found at AstDys. The single-opposition asteroids (for which uncertainties are not given) are listed in the bottom part of the table.

Asteroid	a (au)	e	i (°)	Ω (°)	ω (°)	M (°)
	σ_a	σ_e	σ_i	σ_Ω	σ_ω	σ_M
(5438) Lorre	2.745 726 8384	0.276 342 3275	26.573 949 88	298.516 464 10	238.574 671 76	53.563 784 15
	0.000 000 0219	0.000 000 1256	0.000 012 31	0.000 018 93	0.000 026 67	0.000 023 19
(208099) 2000 AO_{201}	2.747 330 0263	0.327 683 7375	24.271 129 23	276.313 659 13	264.964 258 96	214.380 441 04
	0.000 000 0680	0.000 000 1692	0.000 021 16	0.000 035 03	0.000 052 59	0.000 049 12
2001 RF_{42}	2.745 058 5299	0.301 321 9481	26.030 944 69	335.009 466 24	290.684 543 99	156.889 498 96
	0.000 000 1903	0.000 006 0800	0.000 172 10	0.000 071 68	0.001 244 00	0.000 419 20
2001 XF_{167}	2.745 565 7272	0.331 914 4657	24.311 872 10	265.986 660 39	263.958 503 31	43.553 444 79
	0.000 000 1722	0.000 001 0250	0.000 057 21	0.000 057 38	0.000 433 00	0.000 269 90
2003 BW_5	2.749 282 6344	0.164 223 7556	29.718 642 89	327.572 532 27	185.458 683 14	348.047 655 30
	0.000 000 6285	0.000 005 4500	0.000 187 90	0.000 067 04	0.007 174 00	0.005 137 00
2003 YY_{120}	2.749 243 7940	0.212 723 2504	28.477 910 27	313.196 915 27	219.293 583 80	255.468 898 35
	0.000 019 9500	0.000 016 7200	0.000 280 20	0.000 052 37	0.004 432 00	0.008 961 00
2005 YD_{18}	2.746 902 6458	0.331 568 5526	24.266 238 85	260.563 264 51	270.398 277 90	73.874 042 82
	0.000 001 7310	0.000 003 3110	0.000 081 39	0.000 069 75	0.000 860 10	0.000 321 90
2006 AL_{16}	2.745 814 5602	0.189 085 9883	29.176 566 54	320.046 522 07	207.879 492 79	111.907 101 09
	0.000 003 7100	0.000 004 4950	0.000 119 30	0.000 051 57	0.004 596 00	0.003 942 00
2006 RM_{98}	2.744 751 5579	0.335 403 9030	25.708 060 90	17.596 309 58	272.870 320 56	107.977 899 40
	0.000 001 6040	0.000 001 4330	0.000 095 35	0.000 062 96	0.000 237 50	0.000 344 40
2007 BJ_{62}	2.744 759 3567	0.224 789 4021	28.364 975 67	331.144 707 20	224.853 765 31	9.523 324 79
	0.000 015 1200	0.000 002 6950	0.000 277 40	0.000 043 50	0.001 759 00	0.002 321 00
2008 AD_{104}	2.749 699 7978	0.288 407 3048	25.974 234 65	292.701 305 74	243.434 140 72	289.508 494 64
	0.000 000 4817	0.000 013 2900	0.000 478 30	0.000 070 45	0.002 157 00	0.000 961 90
2010 CG_{176}	2.744 222 7579	0.325 193 0245	24.672 676 83	325.684 074 81	268.766 800 08	109.025 117 41
	0.000 061 6600	0.000 018 3400	0.000 246 60	0.000 069 77	0.000 624 10	0.003 119 00
2011 FQ_{151}	2.744 844 5904	0.301 717 8312	25.911 275 78	342.128 602 92	250.332 664 40	51.865 638 23
	0.000 000 5331	0.000 000 4595	0.000 052 90	0.000 061 77	0.000 184 70	0.000 086 33
2010 AX_{32}	2.745 541 5640	0.190 094 9595	29.192 264 79	304.422 594 05	204.527 027 85	151.892 676 73
2006 VZ_{122}	2.746 462 0372	0.326 111 7058	24.640 779 04	247.419 892 38	280.286 813 78	352.798 626 40
2008 BB_{10}	2.747 178 9321	0.211 852 4243	28.546 308 27	321.494 280 79	220.235 732 22	296.430 853 57
2008 DE_8	2.743 982 4242	0.286 296 5047	26.499 420 06	328.299 348 93	295.692 426 79	238.324 121 35
2010 EW_{42}	2.745 018 7057	0.276 014 7066	27.131 032 88	354.383 661 96	241.265 153 84	116.015 755 14
2010 EJ_{81}	2.745 551 0601	0.326 044 8227	25.331 799 96	356.597 853 42	263.300 304 08	108.509 023 98

Table 4. Different characteristics of the Lorre cluster members.

Asteroid	H (mag)	$p_v \pm \sigma_A$	$D \pm \sigma_D$ (km)	$(\mathrm{d}a/\mathrm{d}t)_{\max}$ (au Myr^{-1})
5438	11.4	0.069 ± 0.002	30.1 ± 0.4	1.5×10^{-5}
208099	14.8	0.052 ± 0.008	6.1 ± 0.1	7.5×10^{-5}
2001 RF_{42}	16.5	0.060 ± 0.024	2.3 ± 0.2	2.0×10^{-4}
2001 XF_{167}	15.8	–	–	1.2×10^{-4}
2003 BW_5	16.3	–	–	1.4×10^{-4}
2003 YY_{120}	15.6	0.045 ± 0.021	4.3 ± 1.2	1.0×10^{-4}
2005 YD_{18}	16.3	–	–	1.4×10^{-4}
2006 AL_{16}	16.4	0.058 ± 0.021	3.0 ± 0.3	1.5×10^{-4}
2006 RM_{98}	16.4	0.036 ± 0.003	3.7 ± 0.1	1.2×10^{-4}
2007 BJ_{62}	16.1	–	–	1.3×10^{-4}
2008 AD_{104}	17.0	–	–	2.0×10^{-4}
2010 CG_{176}	17.9	–	–	3.1×10^{-4}
2011 FQ_{151}	15.9	–	–	1.2×10^{-4}
2010 AX_{32}	17.1	–	–	2.0×10^{-4}
2006 VZ_{122}	15.8	–	–	1.2×10^{-4}
2008 BB_{10}	17.6	–	–	2.7×10^{-4}
2008 DE_8	16.5	–	–	1.6×10^{-4}
2010 EW_{42}	17.1	–	–	2.0×10^{-4}
2010 EJ_{81}	18.6	–	–	4.2×10^{-4}

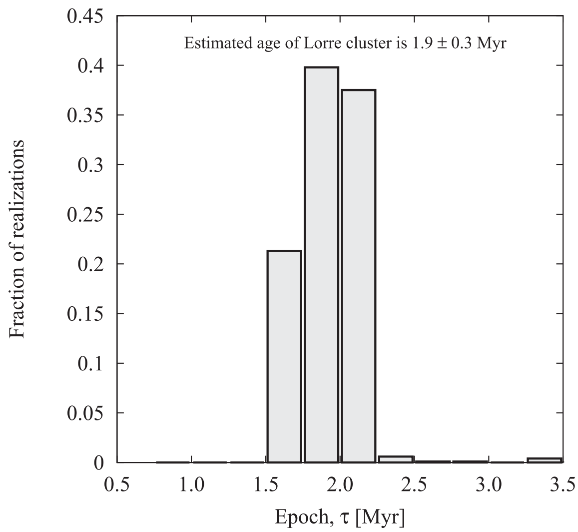

Figure 3. The histogram of possible ages of the Lorre cluster. It is constructed using 10^6 different combinations of clones (see the text). The age of cluster derived from these values is 1.9 ± 0.3 Myr.

2.4 Physical and spectral characteristics

As for physical properties, the geometric albedos (p_v) have been determined for six members of the Lorre cluster (Masiero et al. 2011; Usui et al. 2011), with an average value of 0.053, compatible with *C*-class objects.

Unfortunately, little is known about the spectral reflectance properties. To date, a spectral class has been determined only for the largest asteroid (5438) Lorre, which is classified as a *C*-type asteroid (Bus & Binzel 2002).

It is interesting to note that for this asteroid, an estimate of the rotational period *P* is also available. According to Behrend (2011), *P* is about 25 h. This unusually long period might be, at least partly, the result of angular momentum transfer during the impact

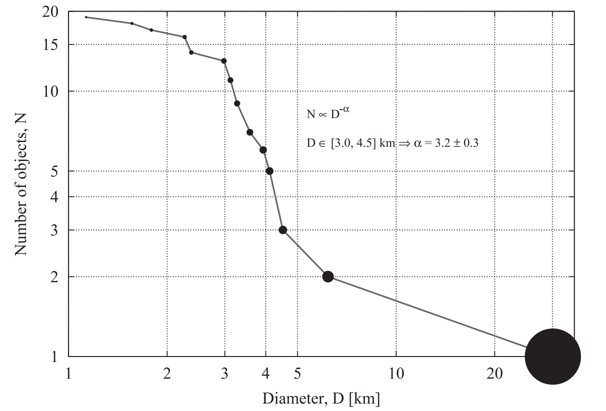

Figure 4. Cumulative size distribution $N(> D)$ of 19 asteroids belonging to the Lorre cluster.

(Dobrovolskis & Burns 1984; Cellino et al. 1990; Takeda & Ohtsuki 2009) that may produce in some cases despinning of mid-sized objects.

2.4.1 *Size of the parent body*

To further characterize the event which produced the Lorre cluster, we estimated the size of the parent body. The simplest way to achieve this goal is to estimate the volume of the parent body by summing up the volumes of all known members, assuming a spherical shape for all of them. For this purpose, we used the available diameters of the objects obtained by thermal radiometry observations, using WISE data in all cases given in Table 1, but for Lorre itself, whose diameter is known from *AKARI* observations. For the objects lacking a size estimate (the majority of the objects in our sample), we derived it using the well-known relation between diameter, absolute magnitude and albedo (see below).

We adopted for each object the nominal value of its absolute magnitude *H* taken from the AstDys catalogue (these data are also listed in Table 1). One should be aware that the catalogue values of *H* are known to be affected by large uncertainties for objects in this magnitude range (Muinonen et al. 2010). This also affects negatively the errors in the albedo determined by means of the thermal radiometry technique, and for this reason we tend to believe that the nominal values listed in Table 1 for WISE- and *AKARI*-derived albedos may well be quite optimistic in some cases. For each object lacking an albedo measurement, we adopted the average value of 0.053 for this family, which is based on the nominal values shown in Table 1. From *H* and the albedo, we can derive the size from the relation $\log(D) = 3.1236 - 0.2H - 0.5\log(p_v)$, where *D* is the diameter. The obtained *D* values range between 1.1 and 4.1 km.

By summing up all the resulting volumes of the family members, we find that the parent body was just a little larger than the largest fragment,[8] (5438) Lorre, which has an estimated diameter of about 30 km. This conclusion does not change if we simply assume that the parent body could not be smaller than the sum of the sizes of the two largest family members. This is the criterion applied by

[8] The difference among diameters of the parent body and largest fragment is smaller than the uncertainties of these two values.

Tanga et al. (1999), and it is based on simple geometric considerations, which is more suitable to treat the cases of full parent body disruption.

The escape velocity from a surface of a 30-km body is about 13.5 m s^{-1} (assuming a density of 1.5 g cm^{-3}, typical of *C*-class asteroids). The second largest member of the cluster, the asteroid (208099) 2000 AO_{201}, is about 6 km in diameter. The cluster turns out to be, therefore, the outcome of a cratering event, which was not sufficiently energetic to completely disrupt the parent body. This result supports our conclusion that the observed asymmetry of the cluster is likely a consequence of the original EVF.

2.4.2 *Ejection velocity field*

The structure of the families in the space of proper elements can be used to infer some information on the ejection velocities of the fragments in family-forming events (Zappalà et al. 2002). As we already noted, the most important feature of the EVF of Lorre seems to be high asymmetry with respect to the location of the largest member. This, however, is not the only peculiar characteristic of the EVF. A jet-like structure is visible in both (a_p, e_p) and (a_p, $\sin(i_p)$) planes (Fig. 2). This is not unexpected in the case of a cratering event. Jetting is expected to have a chance to occur when two objects collide at high speeds and at high incidence angles (see e.g. Housen & Holsapple 2011). Such a structure is observed in both numerical simulations and laboratory experiments (Yang & Ahrens 1995), but it has not been observed yet among real asteroid families, mainly due to the post-impact evolution of the known groups.

Although a detail study of the EVF is beyond the scope of this paper, we want to emphasize here that there is a clear trend in the velocity–size relationship. This trend is in agreement with previous studies (Cellino et al. 1999) suggesting that smaller fragments are ejected on the average with slightly higher velocities. However, the number of known cluster members is still too small at the moment to analyse this trend in more detail.

Finally, it should be noted that differences in velocities (Table 5) are much smaller than what is usually expected in the cases of dynamical families produced by disruption events. In fact, Lorre seems to be likely issued from a moderate-energy cratering event and is the most compact group known so far among high-inclination families (Novaković et al. 2011).

Table 5. Differences in velocities with respect to the asteroid (5438) Lorre.

Asteroid	Δv_{a_p} (m s^{-1})	Δv_{e_p} (m s^{-1})	$\Delta v_{\sin(i_p)}$ (m s^{-1})	Δv (m s^{-1})
5438	0.0	0.0	0.0	0.0
208099	1.5	3.2	1.5	3.8
2001 RF_{42}	11.7	4.1	7.1	14.2
2001 XF_{167}	0.6	3.2	3.1	4.5
2003 BW_5	2.4	0.5	4.2	4.9
2003 YY_{120}	2.4	6.9	2.3	7.7
2005 YD_{18}	2.1	3.0	2.1	4.3
2006 AL_{16}	3.7	6.9	2.5	8.2
2006 RM_{98}	17.9	1.9	3.7	18.4
2007 BJ_{62}	4.1	6.3	3.3	8.2
2008 AD_{104}	0.4	2.4	1.4	2.8
2010 CG_{176}	7.5	0.2	4.7	8.8
2011 FQ_{151}	8.1	1.2	4.5	9.3
2010 AX_{32}	2.5	12.3	0.3	12.5
2006 VZ_{122}	1.9	6.8	1.3	7.2
2008 BB_{10}	3.9	7.7	1.3	8.7
2008 DE_8	9.3	3.7	4.8	11.1
2010 EW_{42}	7.2	5.7	4.1	10.1
2010 EJ_{81}	19.1	7.1	2.6	20.6

2.4.3 *Size–frequency distribution*

Some important information about the impact physics can be obtained by studying the size–frequency distributions (SFDs) of asteroid families (Tanga et al. 1999; Durda et al. 2007). It is generally found that these distributions can be described by a power law, $N(>D) \propto D^{-\alpha}$. Younger asteroid families generally have steeper SFDs which are generally thought to evolve with time towards shallower trends due to collisional and dynamical erosion of the family. A correct way to fit these distributions, i.e. to estimate exponent α, is to adopt an approach based on the maximum likelihood method applied to bi-truncated Pareto distributions (see Cellino, Zappalà & Farinella 1991; Tanga et al. 1999). However, the number of family members is currently too small to perform such a statistical analysis.

Thus, we used an alternative approach based on the least-squares method[9] to estimate the exponent α. In this way, by fitting the cumulative size distribution, for objects between 3.0 and 4.5 km in diameters, we found α to be 3.2 (Fig. 4). This value is smaller than that expected for typical young asteroid families (Nesvorný et al. 2006b; Parker et al. 2008). Likely, this result is affected by the observational incompleteness, and a real α is somewhat larger. In any case, for a moment, we can only say qualitatively that the cumulative size distribution does not appear to be very steep.

2.4.4 *Collisional lifetime*

It is interesting to estimate what was the expected collisional lifetime of the Lorre cluster parent body. This computation depends on many parameters, including mainly the inventory and size distribution of the possible impactors, the average impact velocity and, for what concerns the outcomes of the collisions, on the impact strength of the body, which in turn depends on its size and density.

We computed the mean intrinsic collision probability and the mean impact velocity for the collisions between (5438) Lorre and other main-belt asteroids using the approach of Dell'Oro & Paolicchi (1998). The mean impact velocity results to be about 10 km s^{-1}, due to the high-inclination orbit of (5438) Lorre. Under standard assumptions on the cumulative size distribution of the population of possible projectiles, described by a power law with an exponent of 2.5, a density value of 1.5 g cm^{-3}, and setting the impact strength on the basis of the results of Benz & Asphaug (1999), the estimated collisional lifetime of (5438) Lorre is 6.6 Gyr, in agreement with results of some independent studies (Bottke et al. 2005). This relatively high value does not change much by steepening the size distribution of the projectiles (the lifetime becomes 5.3 Gyr if the power-law exponent is increased to the value of 3.0), nor by changing the value of the density.

The asteroid Lorre is isolated, and there are no asteroids of similar size in its surroundings which might have been produced by

[9] This approach, despite being widely used, is not correct strictly speaking. In particular, this method may significantly underestimate the uncertainties of obtained values. However, as in any case the number of known members is too small to obtain a highly reliable result, we used this method because of the simplicity of its implementation.

the disruption of a hypothetical common parent body. We are led therefore to conclude that Lorre could be a pristine asteroid, which survived nearly intact since the time of its formation. This makes its analysis even more interesting.

3 SUMMARY AND CONCLUSIONS

Here we show the first example of a young asteroid cluster located in a dynamically stable region, which was produced by partial disruption of a primitive body about 30 km in size. We estimate its age to be only 1.9 ± 0.3 Myr; thus, its post-impact evolution is very limited. The large difference in size between the largest object and the other cluster members means that this was a cratering event. The parent body had a large orbital inclination and was subject to collisions with typical impact speeds higher by a factor of 2 than in the most common situations encountered in the main belt. For the first time, we have at our disposal the observable outcomes of a very recent event to study high-speed collisions involving primitive asteroids, providing very useful constraints to numerical simulations of these events (Michel et al. 2003; Jutzi et al. 2009; Leinhardt & Stewart 2012) and to laboratory experiments (Housen & Holsapple 2011).

This is the best preserved young asteroid family produced by partial disruption of a primitive asteroid, of a kind which is supposed to have survived nearly unaltered since the epoch of formation of the Solar system. Being young and well distinct from the background population, this cluster provides very useful information that can help to answer several long-debated questions in planetary science. Examples include a better understanding of impact physics, material strength and the role of space weathering. These processes, highly dependent on the composition of the objects, are so far poorly constrained for primitive asteroids.

Among the members of the Lorre cluster, there are several asteroid pairs, couples of objects with nearly identical orbital parameters. These pairs may well consist of couples of fragments which were ejected with nearly identical ejection velocities. Another possibility is that they might actually be the components of former binary systems originally produced by the collision and later decoupled by some mechanisms (Pravec et al. 2010). Production of binary systems in collisional events has been suggested by numerical simulations (Michel et al. 2001; Durda et al. 2004), but their expected abundance in asteroid families has not been firmly established yet. The young age of the Lorre cluster as well as its sharp separation from background objects may potentially help to better understand both populations, binaries and pairs.

An interesting possibility for future work comes from a recent result of Benavidez et al. (2012) who found that low-energy impacts on to rubble-pile and monolithic targets produce different features in the resulting SFD, and thus, this is a potentially diagnostic tool to study the initial conditions just after the impact and the internal structure of the parent bodies of asteroid families. According to Benavidez et al. (2012), cratering events, produced by small impactors, can potentially provide even more information about the internal structure of the parent body than catastrophic or supercatastrophic events produced by large impactors. Thus, the Lorre cluster seems to be a very promising candidate.

Next, the Lorre cluster may be very useful to improve our knowledge about space weathering processes acting on primitive bodies, a debated subject since results based on the Sloan Digital Sky Survey broad-band photometry (Nesvorný et al. 2005) are not consistent with the results of some laboratory experiments (Brunetto 2009).

Finally, the cluster may be a very interesting place to search for new main-belt comets (MBCs).[10] A recent finding by Novaković, Hsieh & Cellino (2012) supports an idea that these kinds of objects may be preferentially found among the members of young asteroid families (Nesvorný et al. 2008; Hsieh 2009). In this respect, the members of the Lorre cluster are particularly interesting candidates because their heliocentric distances are smaller than those of currently known MBCs. Thus, they may provide a clue about the inner edge of the populations of MBCs.

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[10] MBCs are objects dynamically indistinguishable from main-belt asteroids, but which exhibit comet-like activity due to the sublimation of volatile ice (Hsieh & Jewitt 2006).

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