Recent collisional jet from a primitive asteroid

Bojan Novaković, Aldo Dell’Oro, Alberto Cellino and Zoran Knežević

1 Department of Astronomy, Faculty of Mathematics, University of Belgrade, Studenski trg 16, 11000 Belgrade, Serbia
2 INAF, Osservatorio Astrofisico di Arcetri, Largo Enrico Fermi 5, 50125 Firenze, Italy
3 INAF, Osservatorio Astronomico di Torino, via Osservatorio 20, 10025 Pino Torinese, Italy
4 Astronomical Observatory, Volgina 7, 110 60 Belgrade 38, Serbia

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ABSTRACT
Here 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 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: celestial mechanics, minor planets, asteroids, methods: numerical

1 INTRODUCTION
The asteroid population, being steadily subject to a process of collisional evolution (Davis et al. 1989; Bottke et al. 2003; Morbidelli et al. 2009; Asphaug 2009), provides excellent possibilities to study 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 to 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 has 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 2005), (ii) semi-major axis drift due to Yarkovsky effect (Farinella & Vokrouhlický 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 2010; Delisle & Laskar 2012).

In this respect, little altered recently born families may provide more direct information about the physics of breakup events. Evidence of recent collisions in the asteroid belt have been reported in the last decade and our knowledge about young asteroid families has been increased significantly (Nesvorný et al. 2002b; Nesvorný, Vokrouhlický, & 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 internal structure of the parent body (Jutzi et al. 2009). Because of these reasons it is necessary to identify also young C-class families in dynamically stable regions, because 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 both located in dynamically unstable region (Nesvorný et al. 2003; Novaković 2010). Thus, despite their young ages, these families evolved significantly since post-impact situation. Most of the asteroids belonging to Beagle family (Nesvorný et al. 2008), which is probably less than 10 Myr old, are located in dynamically relatively stable region. However, this group...
is embedded in the large Themis family making 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 Emilikowski 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 expected for C-type objects. For example, geometric albedo of asteroid (14627) Emilikowski is 0.2013 ± 0.0170 (Masiero et al. 2011).

Thus, it is of extreme importance to identify young families, that belong to the most primitive C class, that do not suffer from 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 color 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 dynamical 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 applications (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: semi-major 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

$$d = n_d p \sqrt{\frac{1}{4} (\delta a_p)^2 + 2(\delta e_p)^2 + 2(\delta \sin(i_p))^2}$$

(1)

where $n_d p$ is the heliocentric velocity of an asteroid on a circular orbit having the semi-major axis $a_p$, $\delta a_p = a_p1 - a_p2$, $\delta e_p = e_p1 - e_p2$, and $\delta \sin(i_p) = \sin(i_p1) - \sin(i_p2)$, where the indexes (1) and (2) denote the two bodies under consideration. The HCM connects all objects whose mutual distances (expressed in meters 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 $23 < i < 31^\circ$. The number of asteroids includes numbered, multi- and single-opposition objects found in the recent version of catalogs of osculating elements retrieved from the AstDys web page. Then, we applied the HCM to this set of proper elements, and we analyzed 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, 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$^{-1}$.

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).

| Asteroid | $a_p$ [au] | $e_p$ | $\sin(i_p)$ | $n$ [1/yr] | $g$ [1/yr] | $s$ [1/yr] |
|----------|------------|-------|-------------|------------|-----------|-----------|
| 5438     | 2.74732    | 0.26290 | 0.47230     | 79.0466    | 9.4868    | -9.7809   |
| 2006 AL  | 2.74631    | 0.26318 | 0.47193     | 79.1514    | 9.4935    | -9.7482   |
| 2006 RM  | 2.74544    | 0.26333 | 0.47198     | 79.1277    | 9.4987    | -9.7364   |
| 2008 DE  | 2.74490    | 0.26318 | 0.47193     | 79.1313    | 9.4855    | -9.7550   |
| 2010 CG  | 2.74556    | 0.26292 | 0.47195     | 79.1313    | 9.4855    | -9.7550   |
| 2010 EW  | 2.74732    | 0.26290 | 0.47230     | 79.0466    | 9.4868    | -9.7809   |
| 2011 FQ  | 2.74261    | 0.26276 | 0.47201     | 79.2495    | 9.4847    | -9.6157   |
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1 Although the orbits of single-opposition objects are less reliably known, we used them as well in order to find as many cluster members as possible.

2 Asteroids Dynamic Site: http://hamilton.dm.unipi.it/astdys2/
The orbits of the asteroids belonging to the Lorre cluster are characterized by the moderate eccentricities ($e_p \approx 0.26$) and high inclinations ($i_p \approx 28^\circ$), but the region occupied by these asteroids is not under 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 MMR 3J−1S−1A resonance that is marked with the gray-dashed line, except in the case of $3J$−$S$−$1A$ resonance that is marked with the gray-shaded region. In the top panel basic information about parent body are also given.

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 ($i_p \approx 28^\circ$), but the region occupied by these asteroids is not under 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 MMR 3J−1S−1A resonance that is marked with the gray-dashed line, except in the case of $3J$−$S$−$1A$ resonance that is marked with the gray-shaded region. In the top panel basic information about parent body are also given.

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$^{-1}$, argument of perihelion $\omega \approx 90^\circ$, and true anomaly $f = 90^\circ$. The ellipses are shown to illustrate distribution of the fragments in the case of isotropic ejection field; however, it is easy to see that the ejection velocity field 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 mean motion resonances are denoted with the vertical dashed lines, except in the case of $3J$−$S$−$1A$ resonance that is marked with the gray-shaded region. In the top panel basic information about parent body are also given.

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

| Asteroid | 4 pla | 7 pla | 7 pla + Ceres | 7 pla + CV | 7 pla + CPV |
|----------|-------|-------|---------------|-----------|-----------|
| 5438     | 107.6 | 41.7  | 35.0          | 27.2      | 26.0      |
| 200999   | 128.1 | 75.4  | 50.6          | 32.5      | 30.7      |
| 2001FP6  | 290.7 | 57.7  | 36.0          | 29.0      | 16.1      |
| 2001XF71 | 82.1  | 48.2  | 31.4          | 35.1      | 30.6      |
| 2003BW5  | 41.2  | 6.7   | 21.8          | 7.9       | 20.5      |
| 2003YV120| 534.8 | 203.3 | 39.9          | 30.0      | 32.7      |
| 2005YJ15 | 32.5  | 38.9  | 29.1          | 25.1      | 20.9      |
| 2006AF16 | 304.0 | 162.1 | 41.5          | 35.8      | 31.4      |
| 2006RN26 | 226.2 | 22.1  | 14.0          | 19.2      | 19.7      |
| 2007BH22 | 289.1 | 219.3 | 39.7          | 34.9      | 35.1      |
| 2008AP14 | 125.6 | 41.6  | 37.8          | 28.6      | 26.0      |
| 2010CG175| 742.9 | 75.1  | 37.4          | 36.9      | 23.0      |
| 2011FG71 | 505.5 | 115.1 | 34.4          | 27.1      | 24.7      |
| 2010AX22 | 1960.0| 198.4 | 40.9          | 35.2      | 31.0      |
| 2006VJ222| 35.4  | 31.8  | 27.5          | 25.1      | 11.5      |
| 2008BS10 | 552.9 | 202.0 | 43.6          | 35.6      | 29.7      |
| 2008DE8  | 4000.5| 83.8  | 37.6          | 35.3      | 31.3      |
| 2010EW42 | 2381.0| 76.0  | 44.6          | 33.7      | 28.8      |
| 2010EW42 | 746.6 | 97.9  | 42.2          | 34.2      | 34.1      |

For this purpose, the masses of Ceres, Vesta and Pallas are set to $4.75\times10^{-5} M_\odot$, $1.30\times10^{-5} M_\odot$ and $1.010\times10^{-6} M_\odot$, respectively (Kuzmanoski, Apostоловска, & Novaković 2010; Baer, Chesley, & Matson 2010). These masses are results of the latest calculations performed by means of the improved methodology. A preliminary estimation of Vesta’s mass provided by Dawn mission (http://dawn.jpl.nasa.gov/mission) perfectly match the results from these two papers, for this object. Due to these

cated at 2.752 au. A somewhat less significant but still relevant are another two 3-body MMRs, namely 1J+4S−1A and 4J+3S−2A (see Fig. 2). Finally, 13J/5A 2-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 (1992) and within the framework of several different dynamical models.

As for most of the purposes, in this part of the main asteroid belt, 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, that 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 dynamical model with seven planets, from Venus to Neptune, is used, the estimated Lyapunov times are noticeably shorter (Table 3), meaning that this model should be used for asteroids located in the region of Lorre cluster. The reasons for the important difference among the results obtained with 4- and 7-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 BW5.

Recently, Laskar et al. (2011) showed that close encounters with massive asteroids may induce chaos in their 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.

Our result generally confirms that obtained by Laskar et al.
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 $T_{\text{Lyap}}$ are longer, than those obtained in the model with 7-planets only. An illustrative example is the only possibly unstable object among the currently known members of the cluster, the asteroid 2003 BW$_5$. Its estimated $T_{\text{Lyap}}$ is only 7 kyr in the dynamical model with 7 planets, but rises to 22 kyr when Ceres is added to the dynamical model. Thus, although 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 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 week chaos may be important. Hence, to explore this possibility and to assess a jet like shape of the cluster, we checked 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 average evolution rates of eccentricity and sine of inclinations to be $1 \times 10^{-4}$ and $5 \times 10^{-5}$ per one million years respectively. These are slow changes that do not seem to be able to significantly change 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 expected changes of eccentricity and sine of inclination are only about $2 \times 10^{-4}$ and $1 \times 10^{-4}$ respectively. By comparing these values with the scales of y-axes in Fig. 2 we concluded that dynamical evolution is negligible.

Looking at Fig. 2 it can be easily realized that distribution of the Lorre cluster members is highly asymmetric with respect to the largest member, 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 semi-major 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. 1). 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 ejection velocity field of the fragments, rather than dynamical post-impact evolution. Thus, this cluster still keeps memory of the original ejection velocity field, 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. 2002h, 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 2008; 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 objects and different possible evolutions of the orbital semi-major axes due to the Yarkovsky effect. For each nominal member of the cluster, except for asteroid (5438) Lorre, we produced a set of 10 orbital clones. These clones are drawn from a formal uncertainty, listed in Table 3, assuming 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 (Botte et al. 2001). The maximum drift in the proper semi-major due to the Yarkovsky force ($\frac{da}{dt}_{\text{max}}$) 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 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 3) that Yarkovsky effect on its orbit can be safely neglected.

The orbits of all clones were numerically integrated backward 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 accounts also for the Yarkovsky effect. To account for the indirect effect of Mercury, its mass is added to the mass of the Sun and the barycenteric 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

$$V = na\sqrt{\left(\sin(i)\Delta\Omega\right)^2 + 0.5(e\Delta\omega)^2}$$

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

The obtained results are shown in Fig. 3. The age of the Lorre cluster turns out to be $1.9 \pm 0.3$ 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.

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6 For single-opposition objects we used the following values for all objects: $\sigma_a = 2.0 \times 10^{-5}$ 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 $\sigma_{\nu} = 5'0 \times 10^{-3}$.

7 For simplicity, the Yarkovsky effect is included in the model as a constant secular drift (inwards or outwards) of the semi-major axis. This approximation seems appropriate for our purpose to characterize the age of Lorre cluster in a statistical sense.
Table 3. The oscillating orbital elements along with their formal uncertainties for Lorre cluster members at epoch 56000.0 MJD as found at AstDys. The horizontal line separates single-opposition from multi-opposition and numbered asteroids. 

| Asteroid   | a [au]   | e       | i [°]  | Ω [°]  | ω [°]  | M [°]  |
|------------|----------|---------|--------|--------|--------|--------|
| (5438) Lorre | 2.747726834 | 0.2763423275 | 26.57304988 | 298.51646410 | 238.58476176 | 53.53678415 |
| (208099) 2000 AO201 | 2.7473303263 | 0.3276833775 | 24.72112923 | 276.31365913 | 264.96524936 | 214.39940140 |
| 2001 RF4 | 2.7450583299 | 0.3012314841 | 26.03094469 | 335.00546244 | 290.68542949 | 166.89499896 |
| 2001 XF167 | 2.7456572722 | 0.3319144657 | 23.34187210 | 205.88666503 | 263.59850031 | 43.50544479 |
| 2003 BW4 | 2.7492826444 | 0.1642237556 | 29.71642829 | 327.57322377 | 258.45686314 | 348.46743550 |
| 2003 YV120 | 2.7492437940 | 0.2127232504 | 28.47910273 | 313.19961527 | 219.29358380 | 255.46898935 |
| 2005 YD84 | 2.7469624584 | 0.3516685526 | 24.26628855 | 260.56128451 | 270.38927790 | 73.30442828 |
| 2006 AL10 | 2.7481546622 | 0.1890958933 | 21.76656454 | 302.04652207 | 207.89749279 | 111.90710109 |
| 2006 RM58 | 2.7447354579 | 0.3345903090 | 20.78066900 | 17.96389958 | 227.87032056 | 107.97799490 |
| 2007 BJ12 | 2.7447559637 | 0.2247888402 | 28.34675676 | 331.44173702 | 224.85376531 | 9.53823479 |
| 2008 AD104 | 2.7499697978 | 0.2848073804 | 25.97423465 | 292.70103574 | 243.43414072 | 289.58496464 |
| 2010 CG70 | 2.7422237579 | 0.3251930245 | 24.87627685 | 325.63847011 | 268.76680808 | 109.95421774 |
| 2011 FQ51 | 2.7444849684 | 0.3017738132 | 25.19212758 | 342.12602922 | 250.33266441 | 51.86568325 |

Table 4. Different characteristics of the Lorre cluster members. 

| Asteroid   | H [mag] | p_v ± σ_p,v | D ± σ_D [km] | (dn/dt)_{max} [au Myr^{-1}] |
|------------|---------|--------------|---------------|-----------------------------|
| 5438       | 11.4    | 0.069 ± 0.002 | 30.1 ± 0.4 | 1.5 ± 10^{-3} |
| 2009F9     | 14.8    | 0.052 ± 0.008 | 6.1 ± 0.1 | 7.5 ± 10^{-5} |
| 2001 RF4   | 16.5    | 0.060 ± 0.024 | 2.2 ± 0.2 | 2.0 ± 10^{-4} |
| 2001 XF167 | 15.8    | -             | -             | 1.2 ± 10^{-4} |
| 2003 BW7   | 16.3    | -             | -             | 1.4 ± 10^{-4} |
| 2003 YV120 | 15.6    | 0.045 ± 0.021 | 4.3 ± 1.2 | 1.0 ± 10^{-3} |
| 2005 YD18  | 16.3    | -             | -             | 1.4 ± 10^{-4} |
| 2006 AL16  | 16.4    | 0.058 ± 0.021 | 3.0 ± 0.3 | 1.5 ± 10^{-4} |
| 2006 RM56  | 16.4    | 0.036 ± 0.003 | 3.7 ± 0.1 | 1.2 ± 10^{-4} |
| 2007 BJ12  | 16.1    | -             | -             | 1.3 ± 10^{-4} |
| 2008 AD14  | 17.0    | -             | -             | 2.0 ± 10^{-4} |
| 2010 CG76  | 17.9    | -             | -             | 3.1 ± 10^{-4} |
| 2011 FQ51  | 15.9    | -             | -             | 1.2 ± 10^{-4} |
| 2010 AX2   | 17.1    | -             | -             | 2.0 ± 10^{-4} |
| 2010 EW27  | 15.8    | -             | -             | 1.2 ± 10^{-4} |
| 2008 BD10  | 17.6    | -             | -             | 2.7 ± 10^{-4} |
| 2008 DI6   | 16.5    | -             | -             | 1.6 ± 10^{-4} |
| 2010 EW22  | 17.1    | -             | -             | 2.0 ± 10^{-4} |
| 2010 EW22  | 18.6    | -             | -             | 4.2 ± 10^{-4} |

Figure 3. The histogram of possible ages of Lorre cluster. It is constructed using 10^6 different combinations of clones (see 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 6 members of the Lorre cluster (Usai et al. 2011; Masiero 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 (Bus & Binzel 2002).

It is interesting to note that for this same asteroid an estimate of the rotational period P is also available. According to Behrend (2011) P is about 25 hours. This unusually long period might be, at least partly, the result of angular momentum transfer during the impact (Dobrovolski & Burns 1984; Cellino et al. 1990; Takeda & Ohtsuki 2009), that may produce in some cases despining of mid-sized objects.
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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 catalog, (these data are also listed in Table 1). One should be aware that the catalog 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 − 0.2 $H$ − 0.5 log($pv$) 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 (5438) Lorre, which has an estimated diameter 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 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, 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 ejection velocity field.

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 (Zappala et al. 2002). As we already noted, the most important feature of the ejection velocity field (EVF) of Lorre seems to be a high asymmetry with respect to the location of the largest member. This, however, is not the only peculiar characteristics 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 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 analyze 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, Cellino, & Knežević 2011).

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 distribution 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 toward shallower trends due to collisional and dynamical erosion of the family. A correct way to fit these distributions, i.e. to estimate exponent $\alpha$, is to adopt an approach based on maximum likelihood method applied to bi-truncated Pareto distributions (see Cellino et al. 1999; 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 to estimate the exponent $\alpha$. In this way, by fitting cumulative size distribution, for objects between 3.0 and 4.5 km

| Asteroid  | $\Delta v_{ep}$ [m/s] | $\Delta v_{ep}$ [m/s] | $\Delta v_{ix}(i_{p})$ [m/s] | $\Delta v$ [m/s] |
|----------|----------------------|----------------------|-----------------------------|------------------|
| 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$_{107}$ | 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$_{106}$ | 3.7              | 6.9                  | 2.5                         | 8.2              |
| 2006 RM$_{58}$ | 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$_{110}$ | 5.9              | 7.7                  | 1.3                         | 8.7              |
| 2008 DE$_{6}$ | 9.3               | 3.7                  | 4.8                         | 11.1             |
| 2010 EW$_{42}$ | 7.2               | 5.7                  | 4.1                         | 10.1             |
| 2010 El$_{3}$ | 19.1              | 7.1                  | 2.6                         | 20.6             |

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

$^8$ The difference among diameters of the parent body and largest fragment is smaller than the uncertainties of these two values.
in diameters, we found $\alpha$ to be 3.2. This value is smaller than expected for typical young asteroid families (Nesvorný et al. 2008; Parker et al. 2008). Likely, this result is affected by the observational incompleteness and a real $\alpha$ 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 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 (Bootke 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.

Asteroid Lorre is isolated, and there are no asteroids of similar size in its surroundings which might have been produced by 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 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, Benz, & Richardson 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 process, 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. 2011). 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 into 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 super-catastrophic 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 broadband photometry (Nesvorný et al. 2005) are inconsistent 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) (Novaković, Hsieh, & Cellino 2012). A recent finding by Hsieh & Jewitt (2006) supports the idea that this kind of objects may be preferentially found among the members of young asteroid families (Nesvorný et al. 2008; Hsieh 2009). In this recent result of Benavidez et al. (2012) how found that low-energy impacts into 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 super-catastrophic events produced by large impactors. Thus, the Lorre cluster seems to be a very promising candidate.

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respect, members of 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 populations of MBCs.

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