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The unusual asteroid 2201 Oljato: Origins and possible debris trail

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ABSTRACT

Potentially hazardous asteroid Oljato has a very eccentric low-inclination orbit of semimajor axis a 2.17 au, placing it just outside 4:1 resonance with Jupiter. Its association with magnetic field anomalies known as Interplanetary Field Enhancements (IFEs) in the solar wind led to speculation of a cometary nature and origin. Spectroscopic work showed that it was instead of silicate E-type typical of the inner asteroid belt or Hungarias. We have investigated the region potentially subject to 4:1 resonant effects and find that resonant pumping of eccentricity e takes place due to the outer planets, with moderate increases in inclination i in non-ejected cases. The outer planets do not, however, cause a change sufficient to move Oljato to its present location from the resonance. With inner planet effects included, the increase in e and i is in most cases reduced, however a diffusion increases, so that such a pumping/scattering mechanism can explain the present orbit of Oljato. IFEs may plausibly be related to a debris cascade involving secondary material along Oljato's orbit. We investigate the dynamics of such inferred meteoroids, finding that planetary encounters cause gaps in their distribution along the orbit. The control case of Eros confirms that encounters are needed to cause the gaps, with slow diffusion of secondary material in their absence.

1. Introduction

Asteroid 2201 Oljato has a number of enigmatic features, among them its present orbit, which is a major focus of this paper. The current osculating elements are listed in Table 1, and its orbit and position near the time of a close approach to Venus on 2015 June 16 are shown in Fig. 1. It was discovered on 1947 December 12 by H. L. Giclas at Flagstaff, and the history of recognition of its dynamical interest is given by Ziokowski (1994). Russell et al. (1984) drew attention to Oljato by finding unusual signatures in the solar wind as measured by the Pioneer Venus spacecraft when the asteroid was inside Venus' orbit and near its node. Detected in the magnetic field, these signatures are referred to as Interplanetary Field Enhancements (IFEs). They are hypothesized to travel outward in the solar wind, and those associated with Oljato have been observed near Venus when Oljato was "upwind" of it much as shown in Fig. 1. Lai et al. (2014) describe in detail their association with Oljato since discovery, attributing their origin to secondary collisions in a debris train accompanying the asteroid. The present view of a collisional origin for the material eventually producing IFEs is supported in the case of Oljato by its passage through the asteroid belt with high relative speed (see Fig. 1) and recent observations of fresh collisional material from other small bodies there (Agarwal et al., 2013).

The initial discovery of IFEs led to the hypothesis that Oljato was comet-like, with its elongated orbit and the possibility of emission of material. Near this time, Clube and Napier (1984) introduced the idea that a group of objects with similar orbits formed a "Taurid-Arietid complex" as remnants of a predecessor large comet, with Comet P/Encke the most prominent member. With $a \approx 2.2$ au, $e \approx 0.85$, $i \approx 11.9^\circ$, and longitude of perihelion $\varpi = \Omega + \omega \approx 160^\circ$, the orbit of P/Encke is somewhat similar to those of Oljato and several other objects known at the time. In a semipopular work examining possible historical evidence for the disrupted comet hypothesis, Clube and Napier (1984) speculated that Oljato was an active and visible comet in early historic times. Ziokowski (1995) supported Oljato's possible membership in the Taurid complex, based in part on the finding of non-gravitational effects as would be expected for a cometary body (Ziokowski, 1994). However, the analysis of several near-Earth asteroids, including Oljato, by Yeomans (1991), found no evidence of non-gravitational effects for Oljato. Hasegawa et al. (1992), noting a separation of Oljato's orbit from Earth of only 0.007 au (this value is comparable to the current value listed as *MOID* in Table 1) noted that meteors could be expected if Oljato was comet-like, and found evidence of three entries in the IAU meteor database, associated with a positive declination radiant in December. More

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Table 1
Osculating orbital elements of 2201 Oljato, from http://neo.jpl.nasa.gov/, cited 2014 June 5.

Element	Name	Value	Error(σ)	Unit
	JD Epoch	2,456,800.5		
a	semimajor axis	2.171860123302457	2.933e−09	au
e	eccentricity	0.7127163540491576	3.5789e−08	
i	inclination	2.523518263325149	8.9059e−06	deg
q	perihelion distance	0.6239398947175762	7.7911e−08	au
ω	argument of perihelion	98.20427605958818	0.00011862	deg
Ω	longitude of node	74.99975650786388	0.00011862	deg
M	mean anomaly	246.7537748433917	1.7025e−06	deg
Q	aphelion distance	3.7197		au
P	period	3.20		year
$MOID$	intersection distance	0.003		au

recent evidence from the Canadian Meteor Orbit Radar (Brown et al., 2010) is lacking: however, the meteor speed was predicted to be only of order 20 km/s, to which radar is not very sensitive.

Oljato was used as the eponym of an orbital behavior class by Milani et al. (1989). Planet-crossing asteroids of Oljato class have irregular changes in a, very large e, low or oscillatory i, $q \lll 1$ au, and $Q < 5$ au, making them Venus–Earth–Mars crossers, with many close encounters with these planets, but not Jupiter crossing and with only distant approaches to it possible. They may also jump between resonances with Jupiter. Milani et al. (1989) furnish an example of the importance of close encounters in the transition of 1862 Apollo from Oljato class to a much lower a and e orbit of Geographos class. This took place about 20,000 years ago due to a close approach to Venus, and resulted in an orbit similar to Apollo's present one, in their calculations. Alinda, the eponym of its Jupiter-resonant class, was found to have transitioned from Oljato class into motion dominated by J3:1 mean motion resonance, apparently through an unidentified close encounter. On this basis it was speculated that Alinda could be an extinct comet, an identification that now seems unlikely given its inner main belt (IMB) S spectral type and high albedo of 0.31.[2] While mentioning the suggestions at the time that Oljato could be an extinct comet, Milani et al. (1989) stressed the complex nature of Oljato class orbits, warning against using dynamics alone as an indication of provenance of current near-Earth objects.

Another approach to investigating the nature of a small body is spectroscopy, which could characterize gaseous emissions or the surface. McFadden et al. (1984) discussed evidence of cometary activity in Oljato, but emission or anomalous reflectivity in the UV observed in 1979 was no longer present in 1984 (McFadden et al., 1993). The spectrum from both wide-band and narrow-band measurements was suggestive of the stony S or E types of the inner solar system, and not similar to the primitive types typical of comets or certain asteroids with a highly likely dynamical origin as comets. Recent spectral measurements combining visible and near-infrared show a strong olivene/pyronexe band near 1 μm wavelength, suggesting a less common Q or Sq spectral class, which is nonetheless very different from that of primitive bodies (Popescu et al., 2014). In classifying radar circular polarization ratios, which are indicative of surface roughness, for 214 near-Earth asteroids, Benner et al. (2008) found Oljato's ratio of 0.31 ± 0.02 to be near both their median and mean (0.34) values. This is close to the typical value of S-class, and also to that the few comets for which values have been measured. Thus it is not diagnostic of the nature of Oljato, while not suggesting anything unusual. IRAS results at http://neo.jpl.nasa.gov give an H magnitude of 15.25, which results in a small diameter of 1.80 ± 0.1 km due to high albedo of 0.4328 ± 0.03 (recently confirmed by NEOWISE, Nugent et al. ArXiv preprint), again more typical of inner solar system stony types than of darker outer solar system bodies such as comets.

The physical evidence appears more consistent with Oljato having originated in the inner solar system than from a cometary source, with its possible debris products and transitory spectral changes more likely to be explained by impacts than by comet-like processes. We now examine the orbit and its evolution to see if they are consistent with an inner solar system origin.

2. Orbit

The sidereal period of Oljato is 1169.085 days, which is 3.20 Earth years or 5.20 Venus years. It is not resonant to low order with either of these planets, and has slightly longer period than that required to be in 4:1 resonance with Jupiter. Close encounters can occur with the inner planets (except Mercury) but the aphelion of 3.7197 au does not permit close encounters with Jupiter. The low inclination of roughly 2.5° allows close encounters to be frequent, to the point that Oljato is on the potentially hazardous asteroid (PHA) list. It further means that when the object traverses the asteroid belt, as it does twice per orbit as is clear from Fig. 1, it is near the densest near-ecliptic part. An inferred method for production of IFEs is secondary collision in a debris stream. Collisions (among other dust production mechanisms) are now known to be more frequent than previously suspected in the asteroid belt (Jewitt, 2012). In the case of Oljato itself, Popescu et al. (2014) infer from the visual-near-infrared spectrum that the surface is rather fresh (and comparable to that of some H and L chondrites), supporting the idea that there may have been recent removal of surface material. Debris streams are inferred to arise from primary collisions, i.e. of other asteroids with Oljato. The debris in Oljato's orbit moves slowly out from the asteroid's position along the orbit, and also transverse to it. The secondary collisions could arise from interactions within the debris stream, or from collisions of the debris stream with asteroids. The latter are expected to be more efficient in producing dust since the higher relative speeds would lead them to be more destructive.

We use orbital dynamics studies to investigate influences on the current orbit, its origin, and the behavior of material in possible debris streams. While the eccentric orbit and possibility of comet-like debris were earlier taken to indicate a cometary origin despite the inclination being low, we present a scenario for the origin of this orbit from the inner asteroid belt. This involves e enhancement through the Jupiter 4:1 (J4:1) resonance, and a migration through a scattering mechanism that we infer to be important for inner solar system objects on eccentric orbits. We then discuss effects of planetary encounters on debris streams. We initiate these discussions with a brief consideration of techniques used.

2.1. Numerical integration techniques

Short-term numerical integrations were done using the JPL Horizons program (Giorgini et al., 2001) accessed through the telnet protocol. Horizons includes relativistic corrections to gravity, and effects from tides, but in the form available, could only do integrations in the short time range of 1600–2200 CE for asteroids. For longer term integrations, Horizons was used to make initial integration conditions, and to check proper functioning of other integration codes. Longer-term integrations were done with the Mercury integrator (Chambers, 1999) in Radau mode. In Mercury we used only gravitational force of the eight planets in all computations. In recent years it has been realized that the Yarkovsky

[2] See 887 Alinda entry at http://neo.jpl.nasa.gov

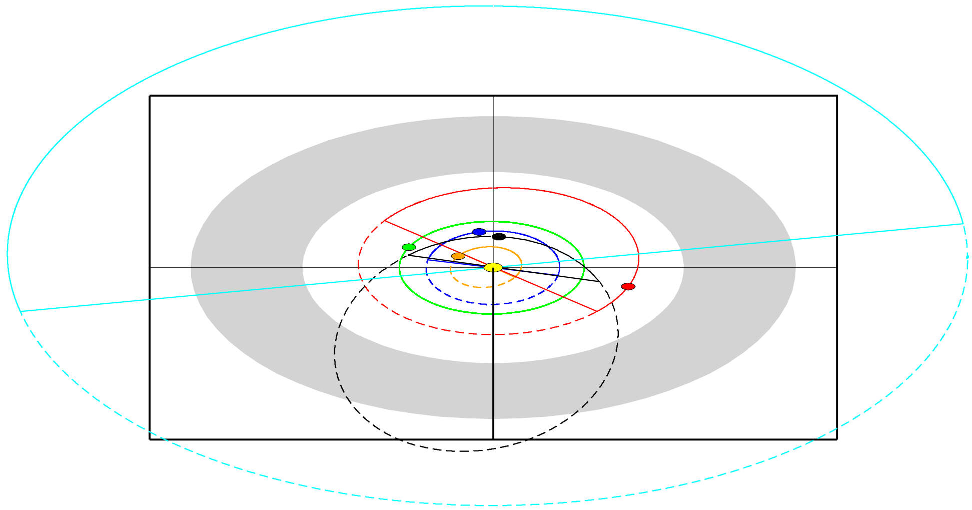

Fig. 1. Orbits and positions (dots) of the inner planets and asteroid 2201 Oljato at perihelion on 2015 May 25. The Sun (not to scale) is in the middle and an outline of dimension 3.7197 au (Q_{Oljato}) square is shown in the ecliptic plane with positive X (vernal equinox) to the bottom. Portions of objects' orbits below the ecliptic are dashed, and the nodes are joined by a straight line. Mercury is shown orange, Venus blue, Earth green, Mars red, and the asteroid black. Portions of Jupiter's orbit and line of nodes are shown in cyan. The nominal asteroid belt location between the J4:1 and J2:1 resonances is shown by grey shading. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

effect of radiation reaction (Farnocchia et al., 2013; Bottke et al., 2006) may cause changes in a in smaller asteroids. This effect depends on physical characteristics of the body in such a way that it may not readily be calculated for a poorly characterized body like Oljato, while this has been successfully done, and compared with observation, for some asteroids (Chesley et al., 2014). The situation is further complicated by the YORP effect, which modifies spin rate, one of the parameters to which the Yarkovsky drift is sensitive. In the case of Oljato, the spin rate is in any case poorly determined, although it may be about 26 h (Popescu et al., 2014).

Of course, the fact that Yarkovsky and YORP effects are difficult to incorporate into modeling does not justify leaving them out. Rather, these small effects have an effective timescale which is longer than that of effects found below. Bottke et al. (2006) find an average drift rate (depending mainly on surface thermal conductivity) of about 10^{-4} au/Myr for km-sized bodies in the IMB. A larger and measured rate was found for 2016 Anza, an IMB object ($a=2.6$ au, $e=0.54$, $i=3.77°$) of diamter 2.6 km, roughly the same size as Oljato. This rate is 10^{-3} au/Myr, although with a rather large standard error of $\pm 9 \times 10^{-4}$ au/Myr (Nugent et al., 2012). The effects we find below take place much faster than this. Bottke et al. (2006) also find that injection into resonance requires the Yarkovsky effect to operate in order to supply the observed delivery rate of near-Earth asteroids. In what follows we do not trace the entry into resonance, but rather make a plausibility argument about the origin of Oljato assuming that it was at one point in the J4:1 resonance. Certainly, the effects we do not include could have dominated the behavior in the low-e pre-injection period, which we did not model. We will address these points again in the Discussion section.

2.2. The present orbit: Jupiter dominance and effects

A plot of the important orbital parameters a and e such as Fig. 2 shows seeming regularities. The pattern is sufficiently irregular that it is clear that the body is essentially not resonant with Jupiter, despite the aphelion $Q=3.71$ potentially bringing it within 1.5 au of that dominant planet. That Jupiter does dominate the perturbations to the motion is clear when one notes that each element of the pattern of repeated increases/decreases in a and e

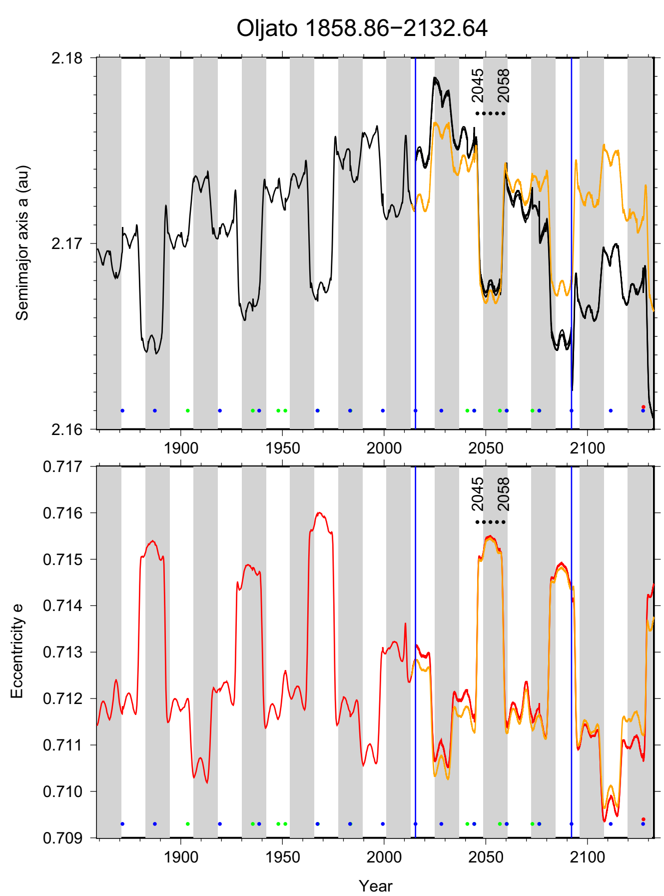

Fig. 2. Variation of a (top panel, black) and e (bottom panel, red) for 2201 Oljato in the near-present epoch. Small dots near the bottom indicate planetary encounters with Venus (blue), Earth (green), and Mars (red) closer than 0.1 au. Vertical lines indicate two close (ca. 0.03 au) encounters with Venus. Vertical striping alternates gray and white at the period of Jupiter. Small dots and labels 2045 and 2058 indicate perihelion times between those years. The multiple curves show the results of the numerical experiment described in the text. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

takes place with a period very close to that of Jupiter (striping added to Fig. 2 emphasizes this). We now draw attention to the details of interaction with Jupiter, which mostly takes place near aphelion of 2201 Oljato. Near the year 2050, the motion is more typical of the general pattern than immediately near the present (this fact arises more from circumstance than from the Venus encounter in 2015 which will be described in more detail below). In Fig. 2, small dots have been placed above the a curve to indicate times of aphelion of 2201 Oljato between the years 2045 and 2058. It is readily seen that there is a decrease in a of approximately 0.01 au immediately after the 2045 aphelion passage, and a slightly smaller increase near the 2058 passage. At three intervening aphelia, the changes of a and e are minimal. The largest effects are separated by approximately one Jupiter period as may be inferred by comparison to the (gray) stripe indicating that period near this time. We proceed to discuss a changes in detail: those of e and other orbital elements could be discussed in a similar manner. In the absence (Murray and Dermott, 1999), (Moulton, 1914), (Schubart, 1994) of a general theory for high eccentricity small bodies, this approach produces insight into important effects.

The position of 2201 Oljato at aphelion in 2045 was determined by inspection of Mercury (Chambers, 1999) output with one day resolution, and approximate positions for subsequent years were found based on its period. These and the orbit in the 2045–2058 time period are plotted in Fig. 3. The slight spread in apogee positions and small changes in the orbit indicated by the thickening of the plot curve are mostly due to overall rotation of the orbit through apsidal and perihelion motion and not further discussed here. Rather we note the positions of Jupiter at these aphelia as indicated by years on the plot, and discuss expected changes in a for 2201 Oljato based on the tangential component of force, much as in Moulton (1914) in the context of lunar theory, and on the disturbing function as in Kaula (1968). We further make the approximation that the motion of Jupiter is slow, even compared to that of the asteroid near aphelia, so that its position

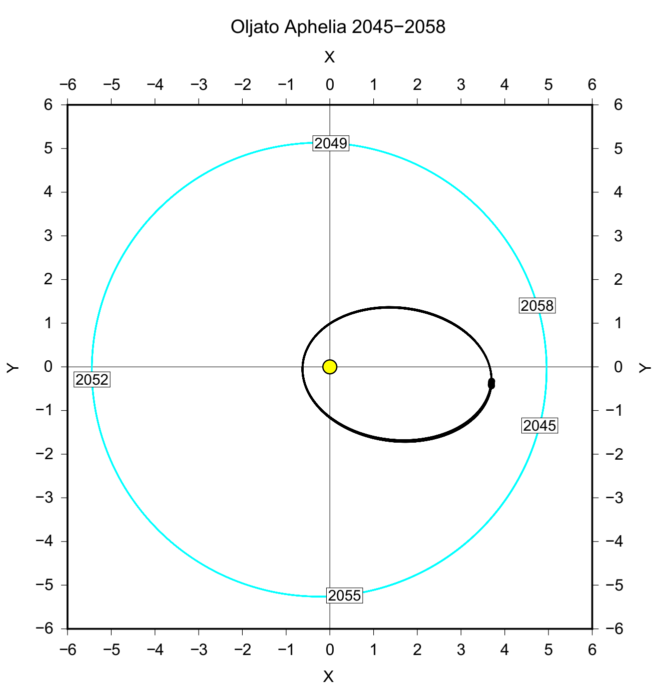

Fig. 3. The positions of 2201 Oljato (black) and Jupiter (cyan) on the dates of Oljato aphelia in the years 2045, 2049, 2052, 2055, and 2058 are shown along with the orbits in this period (some change in Oljato's orbit results in a thickened line and slightly different longitudes at aphelion).

for any given aphelion remains near that of the year number in the plot. The simplest cases are in 2049, 2052, and 2055, when the asteroid remains distant from Jupiter at all points along the orbit, including at aphelion. In these years, perturbative acceleration (including tangential) will be very small, as will any changes in the disturbing function, so that minor change only in a is expected. This conforms well to what is seen in Fig. 2 at those times (indicated by unnumbered dots).

Near the aphelion of 2045, Jupiter is behind 2201 Oljato in its orbit. The tangential force component is negative, which has the effect of decreasing a (Moulton, 1914). In the notation of Kaula (1968), Lagrange's planetary equation for a may be written $\frac{da}{dt} = \frac{2}{na}\frac{\partial F}{\partial M}$, where n is the mean motion, F the disturbing function, and M the mean anomaly. The disturbing function of the asteroid may be written as the sum of direct and indirect terms (Murray and Dermott, 1999). When 2201 Oljato is near aphelion, the direct term is roughly a factor of two larger than the indirect term. The disturbing function is thus positive and dominated by the inverse distance between the two bodies. In 2045, Oljato is moving away from Jupiter when closest and as its mean anomaly M increases, and F by decreasing has a negative derivative in Lagrange's equation. As this time, then, $\frac{da}{dt}$ is consistently negative, for an overall decrease of a during the encounter, consistent with the result from consideration of tangential force, and with the numerical integration.

During the encounter slightly more than one Jupiter period later, in 2058, 2201 Oljato is approaching Jupiter when near aphelion. The tangential component of perturbing force is positive, and the disturbing function increases with M. By either line of reasoning, a increases. In addition, the distance on average is greater than that during the encounter of 2045, so that the increase in a should be slightly smaller than the decrease in 2045. In the short term, one might expect this general behavior (or its inverse) to repeat every Jupiter cycle, explaining the pattern of a increases and decreases seen.

2.3. Planetary encounters

Since its orbit crosses those of Venus, Earth, and Mars, and its inclination is low, 2201 Oljato is subject to encounters with all three. Encounters with Venus or Earth within 0.1 au occur at least once per decade in the present epoch. These encounters are indicated by small colored dots near the bottom of Fig. 2. Those with Mars are not discussed further, and would need to be very close in order to be dynamically significant. In some cases, on the curve above the dot, a small change in a or e can be noted. Larger changes take place in encounters at less than 0.05 au, which are indicated by vertical lines. The only two such encounters in this century are with Venus, the first on 2015 June 16 at 0.0381 au, and the second on 2092 March 05 at 0.0306 au (according to JPL Horizons). The a change in the first encounter is clear at 0.0025 au, while the second shows a more complex structure with a larger change during the event, but with net change of 0.001 au. These are small changes compared to those associated with an aphelion interaction with Jupiter, which often approach 0.005 au. Since there is the possibility of very close approaches to inner planets, while this is not possible in the present epoch with Jupiter, one might expect that eventually there would be large dispersion in a associated with these rare close encounters. We have, however, noted another mechanism by which the orbit of 2201 Oljato can have faster increases in a dispersion.

Since the evolution of orbital parameters of an asteroid with aphelion near the orbit of Jupiter is dominated by its effects (as shown for 2201 Oljato above), we investigated whether small changes imposed near perihelion could be amplified upon subsequent aphelion encounter with Jupiter. To investigate this possibility numerically, we started integrations with Mercury (Chambers, 1999) in Radau mode on 2013 December 25. This is shortly before the first Venus close encounter, a small enough amount of time that small differences between Mercury and JPL Horizons do not build up appreciably before it, allowing a check on the Mercury results. Indeed, before the encounter, the Mercury and Horizons curves (black lines from 2013 on) are indistinguishable. After the encounter, the Mercury and Horizons curves in Fig. 2 are slightly doubled, indicating good but not perfect tracking through it. By chance, the second encounter brings the curves back together again. Having verified that the two codes agreed very well for the standard solar system, we interchanged the masses of Venus and Mercury for the Mercury run beginning in 2003. This has the effect of reducing the mass of the planet encountered by 2201 Oljato on 2015 June 16 by a factor of approximately 15, in turn greatly reducing the effect of the encounter, while keeping the gross properties of the solar system the same on the short timescales considered. In the short period of time before the encounter, the resulting curves overlay the ones with normal order of planets. However, Oljato proceeds through the encounter with a virtually unchanged orbit, as shown by the continuity of the orange curves in Fig. 2. The largest differences from the real case appear in the a behavior, which is significantly different (except, by coincidence, in the 2045–2058 period). The differences are further enhanced after the encounter in 2092 (which took place on the same day, but with much less effect).

We note that at the end of the period shown in Fig. 2, interaction with Jupiter reduced a more for the scattered orbit than for the unscattered (reduced Venus mass) orbit, and even before that the range in a had been increased through "amplification" after Jupiter interaction. Nominally this mechanism would give a larger rate of a diffusion than if inner planet scattering was the only mechanism causing it. Greenstreet et al. (2012) noted that many integration models do not adequately model close encounters, which could include especially those with inner planets. The mechanism we have identified may not have been considered in the past if such encounters are not detected by models, and should be investigated in more detail.

Especially if enhanced through the mechanism we have found, a diffusion plays an important role in understanding the origins of 2201 Oljato. We proceed now to investigate the J4:1 resonance, which could have raised the eccentricity, to later have a diffusion remove the asteroid from the resonance.

3. J4:1 resonant pumping

Moons and Morbidelli (1995) considered the Jupiter J4:1, J3:1, J5:2, and J7:3 mean motion resonances and adjoining secular resonances in a planar system consisting of the Sun, asteroid, Jupiter, and Saturn. In the case of interest here, the J4:1 resonance, they found that large e (0.8 or more) could be attained in the absence (in their model) of inner planets which would remove objects once e became large enough. At this value of a, $e=0.175$ results in Mars crossing, and $e=0.487$ results in Earth crossing. This pumping and removal explains the presence of a Kirkwood gap at the J4:1 resonance and is similar to the situation at the more well-studied J3:1 resonance. The J4:1 resonance region is complicated by the action of the ν_6 secular resonance with the longitude of perihelion of Saturn, and the J3:1 region is in a more populated region of the asteroid belt, so J4:1 appears to have received less attention, and is numerically studied here. The structure of the IMB has been the subject of much interest recently, notably due to the hypothesis of Bottke et al. (2012) of a primordially more populated Hungaria region (the "E-belt") inward of J4:1. Bottke et al. (2012) emphasized the dynamical

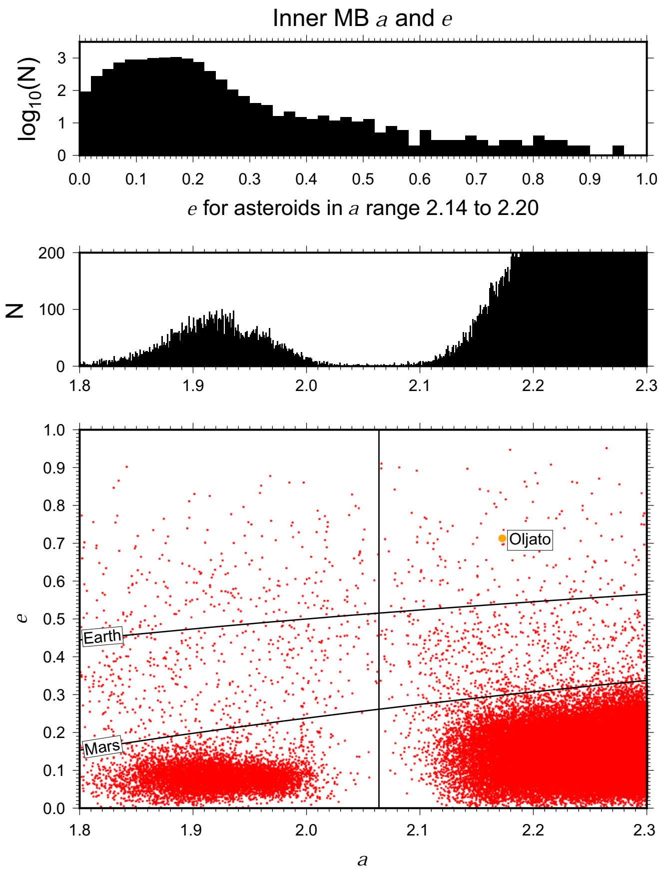

Fig. 4. Structure in a-e osculating element space of the inner main asteroid belt. The bottom panel shows the asteroids in the MCORB database as of September 2013 as red dots, with 2201 Oljato's position shown by an orange dot at upper right. The lower curved line indicates the lower e boundary for Mars crossing, the upper curved line that for Earth crossing. The vertical line marks the exact J4:1 mean motion resonance position. The middle panel is a histogram (linear scale) of number of asteroids in 0.001 au a bins. The top panel is a logarithmic histogram of e in bins of 0.02 for asteroids in the a range near Oljato. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

complexity of the region, and did not specifically start objects in the resonance as we do.

The structure of the IMB depicted by osculating orbital elements a and e is shown in Fig. 4. There is an interesting structure in i as well, but it is not further discussed, as not relevant here except in the sense that most objects have small i, making 2201 Oljato's small inclination not unusual. The dominant feature is the Jupiter 4:1 (J4:1) mean motion resonance, which extends about the vertical line in the lower panel from approximately 2.0–2.1 au. At lower a is the Hungaria region (Bottke et al., 2012), while at higher a the number of objects in the IMB increases rapidly (middle panel). The upper boundary of the IMB is the Mars-crossing line. Hungarias of large a do not approach this boundary closely, which is not further discussed here, but those of smaller a do. In the IMB, less so for Hungarias, there is a density step at the Earth-crossing line also. These decreases indicate the removal of high-eccentricity objects once they start crossing inner planet orbits. A further decrease is not clear at Venus crossing and a line is not shown. However, 2201 Oljato is Venus crossing, and that planet has a large effect on its dynamics as discussed above. The boundaries for the inner belt are also clear in the logarithmic plot of the top panel, at roughly $e=0.25$ and $e=0.5$ for Mars and Earth-crossing, respectively. Although 2201 Oljato is relatively large and was discovered before many of the other high-eccentricity objects in the IMB, it is by no means alone. In early literature it may be that Oljato was thought of as a unique object, but the population of asteroids now known with similar characteristics shows this to be far from true. On the other hand, there is no clear generic relationship of other asteroids to Oljato that we could find, apart from the fact that all objects near the J4:1 resonance at high eccentricity could well have been pumped up in e while in the resonance, and then left it once planet crossing. While the a diffusion that we emphasize here likely removes objects of high eccentricity from the resonance (and secular resonances may also play a role), it is likely that slow processes such as Yarkovsky drift (Bottke et al., 2006) inject them. One can even envisage a sort of Bernoulli principle, with a high-density, slow speed inflow of asteroids into the resonance at near-zero eccentricity, with a higher 'speed', low density flow out due to a diffusion, such that the asteroidal fluxes are equal and Fig. 4 represents a steady state.

The hypothesis tested numerically here is that objects such as 2201 Oljato, with low inclination, high eccentricity, and a slightly greater than that of the J4:1 mean motion resonance, could have once been in the resonance, pumped there to a large value of e which led to a diffusion through interaction with the inner planets (potentially enhanced by the Jupiter interaction amplification described above, although this was not specifically investigated in this part of the study). The mechanism of the test was to run a few clones over an extended period of time, with and without inner planets included in the simulation, and look at outcomes.

These models were run with the Mercury integrator in Radau mode (Chambers, 1999). Cloned asteroids were started with a dispersion of a within the J4:1 resonance range of 2.0–2.1 au, as indicated by absence of asteroids. The initial eccentricity was set to 0.1, much less than the present value, to explore eccentricity pumping (attributed primarily to the J4:1 resonance but arising from all sources in the numerical simulation).

Fig. 5 shows a as a function of time for integrations with only outer planets present. This run was done to check the results of

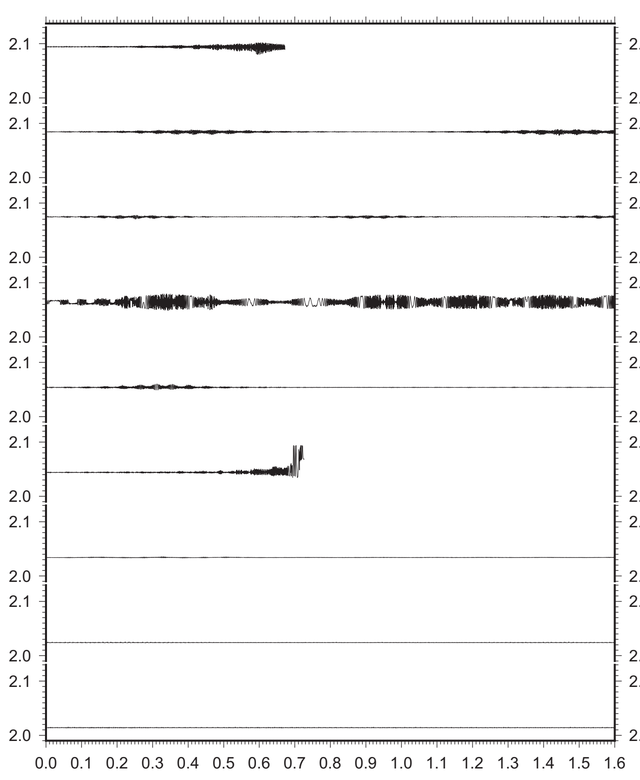

Fig. 5. Development of a in the J4:1 resonance from starting a of 2.014 (bottom) to 2.094 (top), in a simplified Solar System consisting of the four outer planets.

Table 2
Outcomes of Oljato clones started in the J4:1 resonance with and without inner planets.

Initial	Full solar system			Outer planets only		
a	a	e	i	a	e	i
2.014	1.58360	0.451654	6.9541	2.01390	0.135931	15.4477
2.024	1.93771	0.641359	6.2792	2.02402	0.118219	8.5206
2.034	1.96984	0.165053	5.3235	2.03433	0.104899	6.7497
2.044	2.27057	0.997771	22.1709	2.07605	0.997421	26.2809
2.054	1.41160	0.375423	10.1076	2.05366	0.021028	13.7538
2.064	1.75242	0.436752	6.4174	2.07516	0.922453	10.6257
2.074	1.03221	0.180652	6.2437	2.07536	0.383455	0.8214
2.084	1.98709	0.180585	2.6091	2.08289	0.474492	5.1376
2.094	2.06296	0.114933	3.0333	2.09141	0.997534	19.9074

Moons and Morbidelli (1995) that large eccentricity increases could be obtained, and to explore the development of a. Table 2 is used to present e, which is not shown in the figure. In the second last column it is seen that e generally increased from the initial value of 0.1. Near the center of the resonance, an increase to nearly 1.0 (followed by ejection) took place, but for an only slightly increased initial a, a decrease to 0.02. With yet another increment in initial a, a value of roughly 0.92 was attained. In the outer part of the resonant zone, e tended to increase greatly, including to a value near 1.0 (with ejection). In the case of a full solar system, e increased in all cases, again in the center of the resonance attaining ejection. In general, eccentricities were large but less than that of 2201 Oljato at present. We take these results as confirming the finding that the J4:1 resonance can produce large eccentricities, with or without the presence of inner planets. The inclination is shown in the fourth and seventh columns of the table. With values of 20° or greater in cases of ejection, a value of about 6° was typical of the remaining cases. Again, the value attained did not seem greatly affected by the presence or absence of inner planets.

The effects of inner planets were mainly to bring about a much larger dispersion in a. As is clear from Fig. 5, if ejection does not occur, a remains in a very narrow range near its initial value over a timescale of 1.6 million years. Even on the much larger scale of Fig. 6, there is considerably more variation in a. It tends to migrate to lower values with time. Despite this, several clones spend time above $a=2.1$ au, in the range where 2201 Oljato's present osculating a lies.

This study with a limited number of clones confirms that objects starting in the J4:1 resonance can be pumped to large eccentricity values on a timescale of less than one million years (as found by Moons and Morbidelli, 1995). We have not explicitly shown that other effects do not also act to enhance eccentricity, but suggest that on this timescale J4:1 mean motion resonance dominates. During such pumping, the final e and i ranges do not greatly depend on the action of inner planets. One effect of the pumping can be to initiate interaction with the inner planets which leads to diffusion in a. Objects such as 2201 Oljato subject to chaos (which the a amplification mechanism discussed above enhances) cannot have their origins determined on these timescales with any degree of certainty. Nevertheless, even this limited study shows that Oljato's present high-eccentricity, low inclination orbit with a slightly greater than that of the J4:1 resonance may plausibly originate from injection into the resonance by presently discussed slow mechanisms (Bottke et al., 2006) acting on the large population of IMB objects near it.

4. Co-orbital debris

The indirect inference from interplanetary magnetic field measurements that 2201 Oljato was accompanied by co-orbital

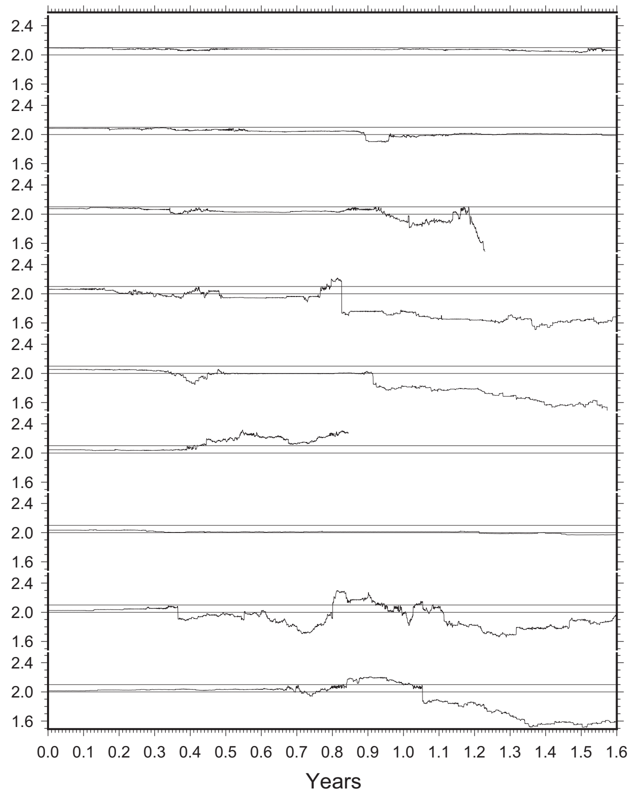

Fig. 6. Development of a in the J4:1 resonance from same starting a as in Fig. 5, in a Solar System consisting of all planets. Note change of scale as compared to that of Fig. 5. Horizontal scale bars at 2.0 and 2.1 au reflect the labeling of Fig. 5 to emphasize this scale change.

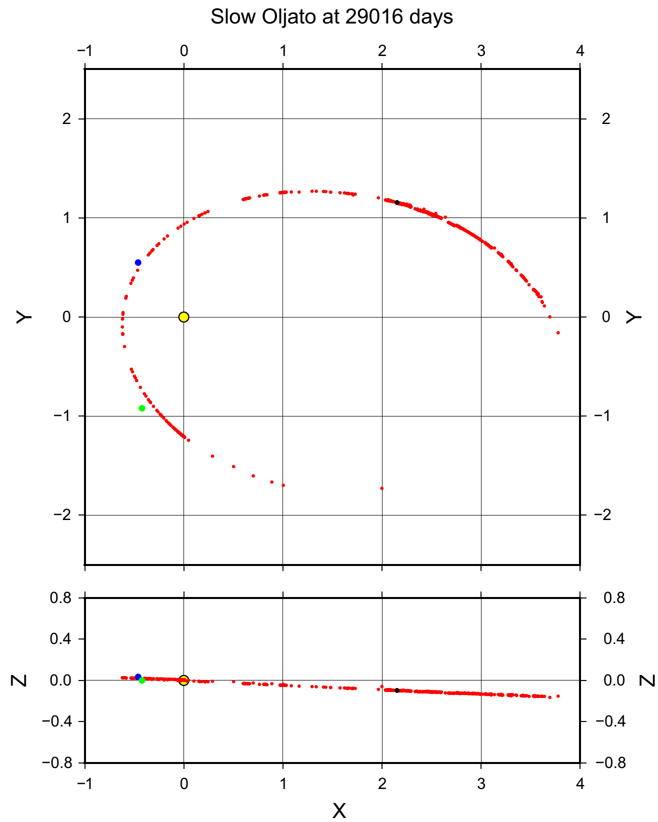

Fig. 7. Oljato (black dot) and its debris trail (red dots) near interaction with Venus (blue dot) in heliocentric XY (top) and XZ (bottom) coordinates. The time shown is May 22, 1679, 79.4 years after debris ejection. The Sun is shown by a large yellow dot, and Earth by a green dot. (For interpretation of the references to color in this figure caption, the reader is referred to the web version of this paper.)

debris stimulated early interest in it, as discussed in the Introduction. Lai et al. (2014) present the latest results on Oljato's Interplanetary Field Enhancements (IFEs), showing that their occurrence rate has decreased on a timescale of decades. Although the mechanism for generation of IFEs is not well understood, they plausibly arise from a collisional cascade in which a debris trail, arising from an initial collision with the asteroid, undergoes further collision and produces dust. Connors et al. (2014) studied the evolution of secondary bodies which may lie along the orbit of asteroid 138175 (2000 EE_{104}). This asteroid is inferred to be associated with IFEs, and is itself an Earth co-orbital. An important aspect of the evolution of a trail of gravitationally dominated meteoroids, if they lie in the orbit of asteroid 138175, is the formation of an irregular distribution characterized by gaps. These gaps were shown to originate from close approaches to Earth and Venus, and in the former case to be resonantly enhanced. Although 2201 Oljato is not resonant with either, it does make close approaches to these planets (and Mars), so that gaps along the orbit could be expected to form. Understanding the spreading of material along the orbit of a body associated with IFEs is important since spatial changes may be detected as temporal changes with the sampling methods presently available. It should be noted that other mechanisms of temporal change, such as removal of dust by non-gravitational effects, may and likely do take place. Much as in the study by Connors et al. (2014), our aim here is to investigate effects in a trail of co-orbitals which are dominated by gravity, i.e. in the 10 m or greater size range. In the collisional cascade picture, such effects would ultimately be reflected in the derived much smaller particles inferred to produce IFEs.

If gaps in a non-resonant asteroid's debris trail arise from close approaches to inner planets, we could expect them to be present in the case of 2201 Oljato, which has such approaches, and absent in the case of 433 Eros, which in the present epoch does not (Michel et al., 1996). Through numerical integration, we demonstrate that this is indeed the case, and confirm that close approaches cause material in general to spread along an orbit more quickly than is the case without such approaches.

Debris was ejected 1 m/s, as in Connors et al. (2014), which may be consulted for further details on physically realistic debris speeds and on setup and integration techniques. The configuration of meteoroids, modeled as having been ejected by 2201 Oljato on December 12, 1599, is shown in Fig. 7 approximately 79.4 years after ejection. This date was chosen to show gap formation during a close encounter of debris with Venus. Numerous other gaps are visible along the orbital path. This confirms that gap formation would be pronounced in a meteoroid trail along the orbit of Oljato, and that the gaps are due to close approaches to the inner planets.

A similar hypothetical debris ejection was associated with 433 Eros, an asteroid which, depite being a “prototypical” near-Earth asteroid interior to Mars, has orbital parmeters ($a = 1.458$ au, $e = 0.0223$, $i = 10.85°$) not allowing close approaches to any planet. Even after 413 years, debris has not spread very far along the orbit, despite the orbital path being shorter than that of Oljato. The 0.7 au spread in this time is consistent with simple relative motion near the ejection speed and there is no evidence of formation of gaps in the distribution. There being no encounters and no gaps is consistent with the picture from 138175 (2000 EE_{104}) (Connors et al., 2014) and the results for Oljato above, indicating that encounters form gaps. In addition, Connors et al. (2014) found enhancement of along-orbit speeds through the encounters, and the much greater spread along the orbit of 2201 Oljato as

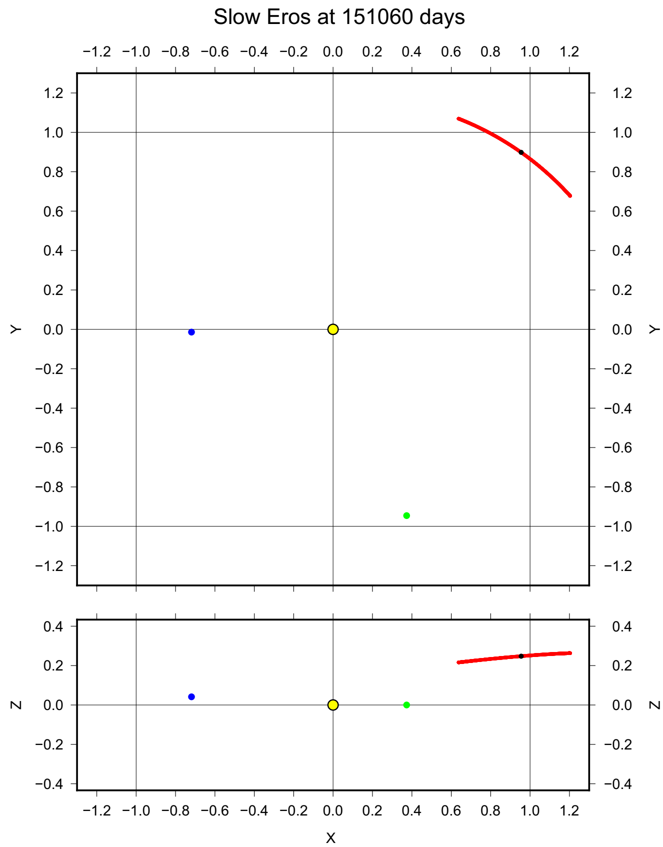

Fig. 8. Eros (black dot) and its debris trail on July 14, 2013, 413 years after debris ejection. Objects are depicted as in Fig. 7, but the scale is changed.

compared with 433 Eros supports the view that encounters enhance spread, i.e. "heat" the debris trail (Fig. 8).

5. Discussion

We discussed in simple terms how a non-resonant orbit with aphelion near Jupiter's orbit can lead to a semi-regular pattern of step-like changes in a and e. A further simple numerical experiment was done by interchanging the masses of Mercury and Venus. Although in the long term this would affect the evolution of the entire solar system, we dealt with only very short-term effects arising from planetary encounters in the twenty-first century. We found that changes in the encounter circumstances in the inner solar system were amplified upon subsequent interactions with Jupiter. This appears to lead to an enhanced diffusion in a as compared to diffusion arising only from inner planet encounters.

We next compared a diffusion for asteroidal clones starting with low eccentricity within the J4:1 resonance, finding that the diffusion was much higher in a case including inner planets than if they are not included. In several of these cases, we found as much as roughly 0.5 au of change in a per Myr, about 10,000 times that (Bottke et al., 2006) which would arise from the Yarkovsky mechanism. These results likely involved deep planet crossing, and we did not determine to what degree Mars crossing alone would affect drift of less eccentric asteroids. Nonetheless, our results suggest an important role for a diffusion induced by planetary encounter.

Planetary encounters, if they occur, were also found to be important in the evolution of debris trails. Despite the small size of bodies that might exist in such trails, and the fact that the Yarkovsky force for meteoroid-size bodies scales approximately as the inverse radius (Bottke et al., 2006), the time evolution in these debris trails is on a timescale of only hundreds of years, so that radiation reaction forces are likely negligible. To understand more clearly the association of debris trails with IFEs it is likely that consideration of dust-size grains is more important than fine detail of the orbital development of the meteoroids in the trails.

In both of these instances involving close encounters, the Radau method is not optimal (Chambers, 1999) and (Greenstreet et al., 2012) found that even other widely used approaches do not adequately model very close encounters. Thus we suggest that further studies be done with more emphasis on their details.

6. Conclusions

We have examined how the association of IFEs with 2201 Oljato led to speculation and research into what originally seemed an unusual orbit, possibly of a modified cometary nature. We show that instead there are numerous objects near Oljato in a-e space, and that the origin of such objects and likely of Oljato itself may be understood in terms of inner asteroid belt processes including (nominally) Yarkovsky drift, resonant pumping of eccentricity, and scattering by inner planets once the eccentricity is high enough. We further found that there is a mechanism allowing small a changes due to inner planet encounters to be "amplified" for eccentric objects with aphelion near the orbit of Jupiter.

In terms of the IFEs that originally elicited interest in 2201 Oljato, we have found that a putative debris trail would form gaps and spread more rapidly than would otherwise be the case, if there are inner planet encounters. We also showed that the inverse is true in the case of 433 Eros, which in the present era does not have encounters, and shows neither gaps nor enhanced spreading in models of a meteoroid trail.

Our overall picture of Oljato thus emerges as an object of inner solar system origin whose eccentricity was pumped up near its present location, followed by drift outward in a. Both of these orbital changes could have taken place while retaining a modest inclination. That modest inclination and large eccentricity lead to high speed passages through the core of the main belt, where we now know through direct evidence that collisions take place. A debris train originating in such a collision may at the present time give rise to IFEs observed radially outward from the Oljato orbit, moving radially after entrainment into the solar wind. The observed decline in IFE rate could be due to gap formation processes along the orbit, although other explanations such as direct removal of dust may also be involved or even dominate.

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