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LETTER TO THE EDITOR

Extremely young asteroid pair (458271) 2010 UM26 and 2010 RN221

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ABSTRACT

Aims. The extremely similar heliocentric orbital elements of the main-belt objects (458271) 2010 UM26 and 2010 RN221 make them the tightest known pair and hold the promise that it is very young. We analyzed the conditions of its origin and determined its age.
Methods. We conducted dedicated observations of (458271) 2010 UM26 and 2010 RN221 in summer 2022 that resulted in a high-accuracy astrometric set of data. Joining them with the previously available observations, we improved the precision of the orbit determination of both asteroids. We used numerical simulations backward in time to constrain the origin of this new pair by observing orbital convergence in Cartesian space.
Results. Using a large number of possible clone variants of (458271) 2010 UM26 and 2010 RN221, we find that they all converge in a narrow time interval around March 2003. They have extremely tight minimum distances (≤1000 km) and minimum relative velocities ($\leq 3\,\mathrm{cm\,s^{-1}}$). These conditions require that the mutual gravitational attraction of the asteroids constituting the pair is included when its age is determined. Extending our model by this effect even improves the convergence results. We find a probability of more than 55% that the pair formed after 2000. However, quasi-satellite captures mean that the possible age uncertainty of this pair might extend to the 1960s. This is by far the youngest known asteroid pair, however. It is a prime target for future astronomical observations.

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

1. Introduction

The main belt of asteroids is by no means a static arena. Instead, evolutionary processes with different timescales permanently sculpt this population into an ever-changing state. Traditionally, mutual collisions were identified to be the prime driver of the main belt evolution, leaving behind traces in the form of asteroid families and occasionally injecting objects into the orbital resonances (thus setting them onto a journey to the planet-crossing population). At the end of the last century, the concept of small-asteroid migration due to thermal accelerations was revisited. This process was found to be more important than collisions in the depletion of the main belt, sustaining the transfer of small asteroids and meteoroids toward the terrestrial-planet zone (e.g., Bottke et al. 2006). Yet a new aspect of the main belt asteroid evolution was found slightly more than a decade ago when Vokrouhlický & Nesvorný (2008) serendipitously discovered a peculiar population of objects on extremely similar heliocentric orbits. They proved that the probability that these objects were so similar as the result of a random fluke was virtually nil and coined the name asteroid pairs for this situation. Vokrouhlický & Nesvorný (2008) suggested that the asteroid pairs may be formed by one of three mechanisms: (i) in a most conventional concept, they were assumed to represent a pair of the largest members in a mini-family (whose other members were not yet detected), (ii) rotational fission of a parent object, or (iii) recent instability of a binary followed by a split of its components. Pravec et al. (2010) used photometric observations of the primary component of the pairs known to date to prove that (ii) is the predominant process that leads to pair formation. This conclusion has only been strengthened in the most complete study yet of the asteroid pairs by Pravec et al. (2019). Nevertheless, the relation to the binary asteroids is deep because it became clear that the asteroid pairs are just failed binaries. Pairs and binaries are both formed by rotational fission of a precursor asteroid, and it is basically details of the fission process (e.g., the component trajectories immediate after the fission event or the exact shape of the pair components) that dictate the outcome (see the review by Margot et al. 2015). Discovery of the asteroid pairs thus complemented a complex picture of the colorful and dynamic life of small asteroids.

The typical age of asteroid pairs, namely the time since their formation, ranges between several thousand to about a million years (e.g., Pravec et al. 2019). Pairs with an older age certainly exist as well, but their orbits become less similar and it is difficult to identify them in the unrelated background population of asteroids. The youngest pairs of main belt asteroids known so far have an age of ≃7 kyr (see Žižka et al. 2016; Kyrylenko et al. 2021). We note that even younger structures exist, such as the pair of near-Earth objects 2019 PR2 and 2019 QR6 (Fatka et al. 2022), or even fission events caught in (or near) action by direct observations (e.g., Jewitt et al. 2015, 2019; Ye et al. 2019). In these cases, objects of cometary nature might be split by other processes, however, that are related to their very weak material strength and/or subsurface volatile activation.

Here we report the discovery of the extremely young asteroid pair of small main-belt asteroids (458271) 2010 UM26 and 2010 RN221. The primary is slightly smaller than a kilometer in size, while the secondary is about 400 m in size (assuming 0.2 geometric albedo and astrometric absolute magnitudes). They are both located in the central part of the main asteroid belt, next to the 3:1 mean motion resonance with Jupiter. The similarity of their orbits is striking even compared with the standard of other known pairs (see, e.g., Vokrouhlický & Nesvorný 2008), and this similarity holds the promise that they are very young. In an attempt to prove their very young age, we first reviewed the available astrometry for both objects, complementing it by recovery of archival frames of the Catalina Sky Survey (CSS) and remeasuring some of the Canada France Hawaii Telescope (CFHT) data. We also performed our own targeted campaign in June and July 2022, from which we obtained very accurate new astrometric observations. With this dataset available, we determined the orbits of the two components in the pair (Sect. 2). Next, we propagated the nominal orbits and a large number of orbital clones within the uncertainty limits of the orbit determination backward in time and monitored their mutual convergence in Cartesian space. Results from this experiment allowed us to statistically assess the epoch of separation of the two components in this asteroid pair (Sect. 3). Finally, we considered further support for the hypothesis that this pair is extremely young and suggest future observations of its components (Sect. 4).

2. Observations and orbit determination

Archived and new astrometric observations for 458271 and 2010 RN221. As a first step, we review available astrometric data for (458271) 2010 UM26 and 2010 RN221. The two asteroids were discovered during their favorable 2010 opposition and were subsequently followed up, mostly with incidental survey astrometry, during their 2014 and 2018 observation windows. The first object, which is brighter, was also incidentally detected by Pan-STARRS in 2016 and 2020, when it was fainter than 22 mag. The second fainter component was below the sensitivity of all major surveys during these poorer observability windows. In addition to this incidental follow-up, precovery observations have been reported to the MPC for both bodies. The larger body has astrometric coverage from 2005 and 2006, and the fainter body has a single listed tracklet from 2005.

With these observations in the MPC database, it is possible to determine the orbits for both bodies well, so that the extreme similarity of the orbits is obvious. However, in order to better understand the dynamics of the pair, we searched for possible additional prediscovery detections of the two bodies. We were able to locate detections of 2010 RN221 during the 2006 apparition in the image archive of CSS, and we extracted accurate astrometry from them, including a formal estimate of the astrometric error bars. In order to ensure the best possible accuracy for the oldest end of the observational arc, which is close to the supposed separation time, we also remeasured the 2005 precovery detections of the two asteroids from the original archival images of CFHT. Our remeasurements were also complemented with properly determined error bars that are not available from the MPC.

Furthermore, the two objects became easily observable for astrometric purposes during the early summer of 2022. We therefore decided to complement the dataset with additional astrometric measurements extending the observed arc to 2022. We observed the field that contained the two objects using the 0.8 m Schmidt telescope at Calar Alto, Spain (MPC code Z84), for five nights between May 28, 2022, and July 9, 2022. The larger body was clearly detectable and measurable on all nights, leading to astrometry with typical error bars of ±0.2″. The smaller body, on the other hand, was only detectable on three of the nights because it was faint and the stellar background was crowded. Nevertheless, astrometry with an accuracy of ±0.3″ was extracted from those nights. These observations, all obtained using *Gaia* DR2 as a reference catalog, are presented in the appendix in Table A.1. Together with the existing data that are available at the MPC for the other apparitions, they formed the basis of the orbital analysis presented in this work.

Orbit determination: initial data at MJD 56700 epoch. Next, we used the `Find_Orb` software (Gray 2022) to derive new orbits for (458271) 2010 UM26 and 2010 RN221. This solution adopted pre-computed JPL planetary ephemerides DE440 (Park et al. 2021). In addition to the barycenters of the eight planetary systems, we also took perturbations caused by the Pluto-Charon system and the three largest objects in the main belt (Ceres, Vesta, and Pallas) into account, whose ephemerides were taken from the JPL Horizons System service[1]. `Find_Orb` provides the best-fit orbital elements and their full covariance matrix for the epoch at the middle of the available observations. While formally the same, we further propagated their orbits to a common epoch MJD 56700 close to the barycenter of individual solutions (Table 1). This was taken as the initial epoch of our convergence efforts, which we describe in the next section.

3. Orbital convergence

After setting the initial conditions for the two components in the (458271) 2010 UM26 and 2010 RN221 pair, we now seek the origin of the pair using the past orbital convergence method. We used the `swift_rmvs4` code, which is part of the well-tested N-body package `swift`[2], for our initial tests. For reasons explained below, our final results were obtained with the more sophisticated N-body integrator known as `SyMBA` (e.g., Duncan et al. 1998). In both cases, we included perturbations from all planets, as well as the largest objects in the main belt (Ceres, Pallas, and Vesta). We used a short time-step of 0.5 day and adapted the time span of the simulation according to its purpose. We both estimated and explicitly verified that thermal accelerations (the Yarkovsky effect) are not needed to be taken into account because this pair is very young. This is an important simplification compared to studies of the origins of other pairs because the thermal accelerations add a number of unknown physical parameters and thus typically increase the age uncertainty.

First, we integrated a large number of clone realizations of the primary (10 000 clones) and the secondary (20 000 clones) over a time span of a century backward in time. Within about half a year interval centered on March 2003, all possible pairs of clones approach at a small distance. The distribution of their minimum distances is quasi-Maxwellian, with a peak value of ≃520 km, a limit that also represents 50% of all cases. Virtually all, namely 99%, clones converge within ≃1000 km. These are satisfactorily low values given the estimated radius of the Hill sphere of $R_{\rm Hill} \simeq 230$ km for the parent body of the studied pair. However, the really distinctive feature of this recent encounter is the extremely low mutual velocity at which any combination of clones approached each other: the highest recorded value was ≃4 cm s^{-1}, but more than 99% of them had a mutual encounter velocity lower than 3 cm s^{-1}, and more than 68% of them had a

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[1] Accessible at https://ssd.jpl.nasa.gov/horizons/

[2] http://www.boulder.swri.edu/~hal/swift.html

Table 1. Osculating orbital elements and their uncertainty as of epoch MJD 56700.0 TT.

Asteroid		a [au]	e	I [deg]	Ω [deg]	ω [deg]	M [deg]	H [mag]
458271	2010 UM26	2.576981320	0.326315921	3.8602822	235.394721	119.126545	313.470031	17.8
	2010 RN221	2.576985942	0.32631528	3.860275	235.394639	119.12674	313.467345	19.2
Uncertainty		δa	δe	δI	$\delta\Omega$	$\delta\omega$	δM	δH
458271	2010 UM26	1.7e−8	6.2e−8	6.1e−6	5.2e−5	5.7e−5	1.5e−5	~0.15
	2010 RN221	4.7e−8	1.7e−7	1.3e−5	9.6e−5	1.1e−4	4.0e−5	~0.15

Notes. Keplerian set of elements used: a semimajor axis, e eccentricity, I inclination, Ω longitude of node, ω argument of pericenter, and M mean anomaly of epoch. The default reference system is that of the heliocentric ecliptic J2000. The orbit determination used JPL DE440 ephemerides, and all observations of the two asteroids from the MPC repository were complemented by our own data (see the appendix). The absolute magnitude values H are provided by the orbit determination solution (i.e., they do not possess high photometric quality).

mutual encounter velocity lower than 1 cm s^{-1}. This is far lower than the estimated escape velocity from the parent body of the pair, some 50 cm s^{-1}. These initial results strongly argue for a very recent split of (458271) 2010 UM26 and 2010 RN221. At the same time, they also call for a more detailed modeling effort. This is because when the two asteroids reach the Hill sphere distance with an extremely low relative velocity, their mutual gravitational interaction must start to play an important role. This is the first time at which the mutual attraction between the components in the asteroid pair contributes fundamentally in the convergence modeling: the work of Vokrouhlický & Nesvorný (2009) was more of a curiosity in this respect, and the work of Kyrylenko et al. (2021) was a correct move toward the concept.

For the remaining part of this section, we therefore switched the integrator to `SyMBA`, which allowed us to account consistently for the mutual gravitational interaction between the asteroids in the pair. Without information about the physical parameters of these bodies, we used their absolute magnitudes and an assumption of a geometric albedo of 0.2 to derive approximate sizes of ≃850 m and ≃430 m. We assumed a bulk density of 2.5 g cm^{-3}. Because the simulations with `SyMBA` are more CPU-extensive, we now used fewer realizations of the two asteroids, namely (i) 400 for 458271, and (ii) 2000 for 2010 RN221. We performed 800 000 simulations considering all possible combinations of these clones. We kept the short time-step of 0.5 days, and integrated for 70 yr backward in time.

As expected, the results from the initial simulation were modified and substantiated by the effects of mutual gravitation attraction of the two asteroids in the pair near the epoch of their orbital convergence. Two interesting cases are shown in Fig. 1. The left panel shows the situation when in our previous run the two clones would miss each other by ≃410 km at the closest approach (blue curve). However, the gravitational focusing causes them to really approach much more closely, to ≃45 km, performing an almost parabolic flyby (red curve). In this situation, the encounter may become delayed by a year. In more regular clone encounters, when even the previous `swift` simulation caused them to approach more closely along a nearly head-on approach, the gravitational focusing advanced the time of the encounter. The right panel of Fig. 1 shows a more extraordinary effect, when the conditions of the pair component approach result in their capture into a quasi-satellite configuration that lasts nearly 40 years. We found that $\lesssim$10% of the clones that converge to a minimum distance below $R_{\rm Hill}$ exhibit a quasi-satellite capture. While small, their importance is large. This is because we must consider the possibility that (458271) 2010 UM26 and 2010 RN221 split at any moment during the quasi-satellite configuration. Overall, more than 27% of all clone combinations result in convergence well below $R_{\rm Hill}$. Little more than 0.6% of the cases lead even to a physical collision of the two asteroids. These numbers increase and decrease with a higher and lower assumed bulk density or larger and smaller size of the parent object of the pair. In any case, however, these are large numbers that support a recent split of the components in this pair.

We now combined the convergence configurations of all considered pairs of clones into a probability density distribution of the pair origin within the past decades (considerations of a possibly older age are postponed to Sect. 4). In practice, we recorded the epoch of all configurations in which the clones were (i) closer to each other than $R_{\rm Hill}$, and (ii) their mutual velocity was lower than 50 cm s^{-1}. We consider their distribution to be a good proxy of the pair origin. This is because effects of nonspherical shapes of the components in the pair or spin-orbit coupling effects during their separation phase may in reality imply that the two asteroids split and separated from the parent body slightly earlier or later than just the formally closest approach in our simplified model. Additionally, the quasi-satellite configurations do not even allow us to determine the moment of the formally closest approach. Again, the complicated shape and spin-orbit effects may imply that the separation occurred at any moment during this phase. Our result is shown in Fig. 2. Some 8% of solutions are concentrated in a peak at 2003.5 ± 0.25. These are simple flybys. Before 2003, the distribution continues with an extended tail back to the 1960s. This is the contribution of (i) the delayed long-lasting encounters (as shown in the left panel of Fig. 1), further convolved with (ii) the quasi-satellite configurations deeper in the past. Although (ii) represents a minority of the solutions, they formally outweigh the flybys in our approach. This is because they last for years, compared to one or two months of the early flyby configurations. Overall, the probability is higher than 55% that the pair formation post-dates 2000 in our simulation. The exact shape of the probability distribution may slightly change when the statistical dependence on several unknown parameters (e.g., bulk density or asteroid size) is included. We defer this modeling to the future, when more is known about the components in the pair from dedicated observation.

4. Discussion and conclusions

Further support of the hypothesis that 458271-2010 RN221 are young. We showed above that the orbits of (458271) 2010 UM26 and 2010 RN221 converge to a mutual configuration that is expected after a fission of their parent body some 20–60 years ago. Here we strengthen the case with further arguments.

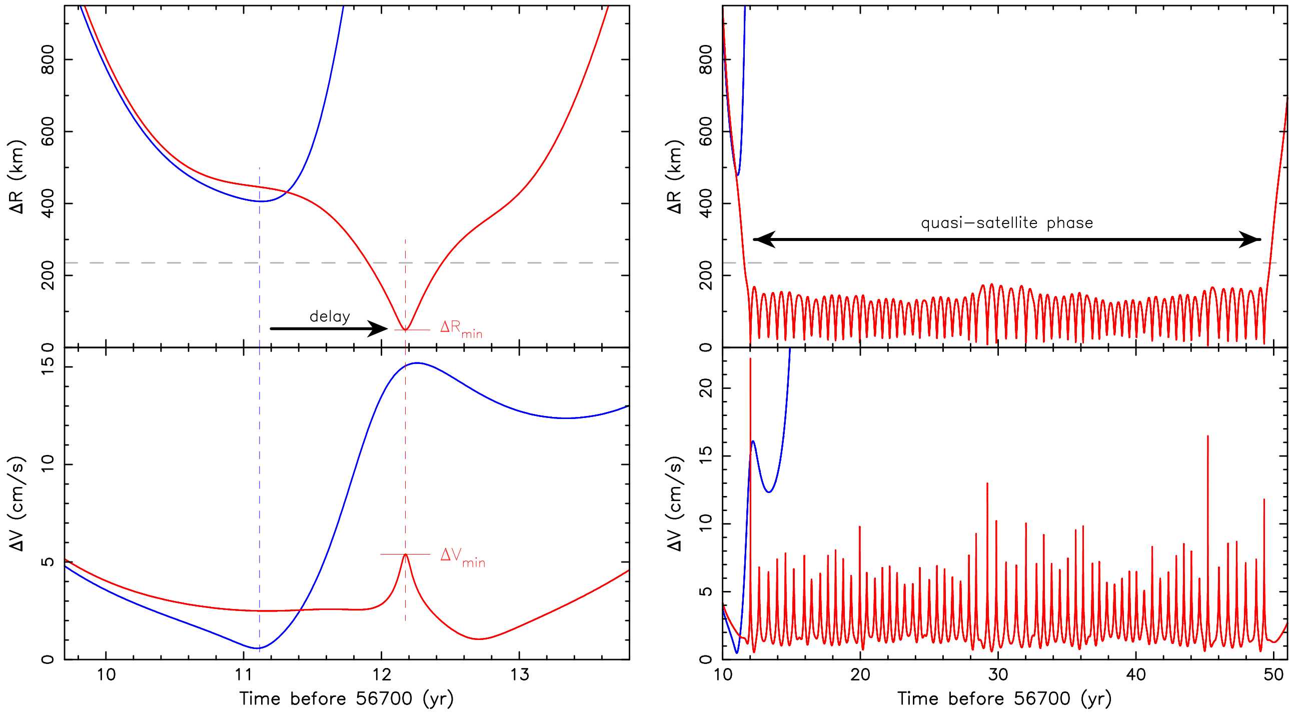

Fig. 1. Two examples of convergence for (458271) 2010 UM26 and 2010 RN221 orbits. The *top panels* show the mutual distance of the two asteroids, and the *bottom panels* show their relative velocity. The abscissa is the time prior to initial conditions of the simulation at MJD 56700.0 (February 12, 2014). Each simulation was run twice, with (red line) and without (blue line) the mutual gravitational attraction of the components in the pair. The dashed gray line in the *top panels* indicates the estimated radius of the Hill sphere of the parent body. The *left panels* show a simple close encounter at a minimum distance of $\simeq$45 km distance. The relative orbit at the closest encounter is an almost parabolic flyby that dove well into the Hill sphere. This effect would have been missed if we had not accounted for the mutual gravitational attraction of the asteroids. The *right panels* show a more complex evolution when the two asteroids were temporarily captured into a quasi-satellite configuration for nearly 40 years. The orbital eccentricity during the quasi-satellite phase is high; the apocenter reaches beyond half of the Hill radius.

First, we show that the configuration at convergence, namely the mutual distance $\leq$1000 km and the relative velocity $\leq$10 cm s^{-1}, to be conservative, is extremely unlikely to occur by chance. To do this, we first determine the intrinsic collisional probability $p_{\rm i}$ averaged over all configurations of asteroid orbits in the main belt. We used the formulation by Greenberg (1982) and more than 91 000 asteroid orbits with an absolute magnitude lower than 15 as a proxy for all asteroids. We obtained $p_{\rm i} \simeq 3.2 \times 10^{-18}$ km^{-2} yr^{-1}. Estimating the number of asteroids that are larger than a kilometer to $N_1 \simeq 1.3{\times}10^6$, and those larger than 400 m to $N_{0.4} \simeq 6{\times}10^6$ (e.g., Bottke et al. 2020), roughly the sizes of the primary and the secondary components in our pair, we now consider how many encounters $N_{\rm events}$ of field asteroids at a distance $R \simeq 10^3$ km (or smaller) we would expect within the past $T \simeq 50$ yr. We obtain $N_{\rm events} = p_{\rm i} N_1 N_{0.4} R^2 T \simeq 1250$ such events. However, the contributing collisional or encounter configurations would have a mean relative velocity of $\simeq$5 km s^{-1}. Using the formulae in Greenberg (1982), we analyzed the distribution of the encounter velocities (see also the detailed discussion of mutual orbital velocities of asteroids in Bottke et al. 1994, namely their Fig. 7 for an idea). We found that encounters with 50 m s^{-1} have a likelihood of slightly more than 10^{-7}, and those with even lower encounter velocities are quite smaller. This shows that a random encounter of the field (unrelated) asteroids with the indicated sizes having the required relative velocity $\leq$10 cm s^{-1} has a virtual probability of zero.

A more difficult task is to show that (458271) 2010 UM26 and 2010 RN221 pair did not form deeper in the past, probably again by a fission of their parent asteroid. Vokrouhlický & Nesvorný (2008) have noted that in orbitally stable regions of the main belt, gently separated bodies may experience a sequence of repeated encounters with a period equal to their synodic orbital cycle (see their Fig. 6). A theoretical possibility would therefore be that (458271) 2010 UM26 and 2010 RN221 separated tens to hundreds of thousands of years ago and experienced a close encounter recently after completing a certain number of synodic cycles. However, perturbations, such as encounters with the largest objects in the belt or differential thermal accelerations, work against this possibility by generically lifting their encounter velocity and separating them at larger distances.

In order to estimate the probability of a long ago origin of (458271) 2010 UM26 and 2010 RN221, we used the method introduced in Sect. 4.3 of Žižka et al. (2016). In particular, we created 10^5 synthetic pairs by separating a test body from the nominal orbit of (458271) 2010 UM26 at the reference epoch MJD 56700. We tested several values of the separation speed from 1 cm s^{-1} to 10 cm s^{-1} because these values confirmed our convergence solutions in Sect. 3, and used an isotropic distribution of the initial relative velocity. The orbital propagation of the separated component, representing 2010 RN221, accounted for the thermal acceleration (the Yarkovsky effect). The maximum semimajor axis drift was estimated using the linearized thermal formulation to $\simeq 5 \times 10^{-4}$ au Myr^{-1} (e.g., Vokrouhlický et al. 2015), and a simple implementation of the thermal acceleration with just a transversal component was used (e.g., Farnocchia et al. 2013, Sect. 2.1). To keep the simulation simple, we used the `SyMBA` setup without the mutual gravitational attraction of the components in the pair. We propagated the orbit of (458271) 2010 UM26 and the ejected particles for

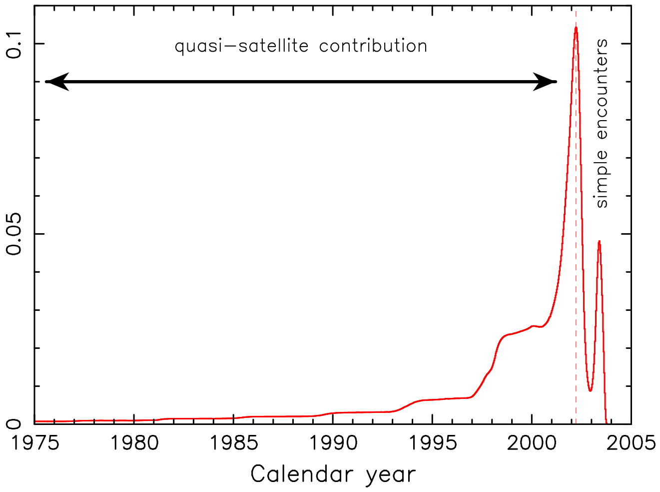

Fig. 2. Probability density distribution of the (458271) 2010 UM26 and 2010 RN221 convergence epoch. The calendar year is given at the abscissa, and the normalization of the ordinate assumes units in days. About 8% of the solutions are concentrated in a narrow peak centered at about 2003.5. These are simple head-on encounters. Longer-lasting encounters, shown in the left panel of Fig. 1, and the quasi-satellite solutions, shown in the right panel of Fig. 1, contribute to the tail that extends beyond the peak to the 1960s.

500 kyr backward in time[3]. We used a short time-step of one day, and at each time step, we monitored the mutual configuration of (458271) 2010 UM26 and each of the ejected particles in Cartesian space. We recorded the epochs in which these synthetic pairs approached below 1000 km and had a mutual velocity lower than 3 cm s^{-1}. This is the limit that virtually all pairs of clones of (458271) 2010 UM26 and 2010 RN221 reached in the past two decades (Sect. 3). We started to record these configurations 10 kyr through our backward integration because we estimated by integrations of real orbits of (458271) 2010 UM26 and 2010 RN221 that the first synodic-cycle approach cannot occur earlier. We found that the convergence criteria set by the recent approach are indeed extremely severe and hard to be satisfied on a longer timescale. In the simulation in which the secondaries were separated by the minimum tested velocity of 1 cm s^{-1}, only about 5% of the clones even approached the postulated criteria. With higher separation velocities, 3 cm s^{-1} and 5 cm s^{-1}, this fraction even drops to about 1.4% and 0.4%, and it becomes negligible for higher separation velocities. Overall, we therefore conclude that the chances that the (458271) 2010 UM26 and 2010 RN221 pair is older than set in Sect. 3 are very low.

Further analysis and importance of the 458271-2010 RN221 pair. The very recent origin of the (458271) 2010 UM26 and 2010 RN221 pair motivates further studies. For instance, it would be very interesting to search for its parent body on archival exposures of large telescopes in the 1990s or earlier. Extrapolation of the primary orbit may serve as a guidance trajectory for this task.

A significant not yet entirely understood result from the study of previously known asteroid pairs is that in all cases with available data, the primary and secondary were found to rotate about the principal axis of the inertia tensor (e.g., Pravec et al. 2019). This means that (i) either the fission process does not trigger a tumbling of the resulting components or that (ii) the internal energy dissipation in small asteroids is very efficient, leading to a damping of the putative tumbling state in $\lesssim$1−10 kyr. The newly discovered and extremely young pair (458271) 2010 UM26 and 2010 RN221 may allow a critical test of these possibilities. We thus strongly recommend future photometric observations of these asteroids with the goal of determining their rotation state. Pravec et al. (2019) also found that some 14% of the primaries in known asteroid pairs are binaries themselves. It would therefore be interesting to search for evidence of binarity of the primary component (i.e., (458271) 2010 UM26). Large-aperture telescopes are needed for both tasks. This is because when they are bright at opposition, the asteroids of the pair reported here are unfortunately in the Galactic plane in the next decade, making observations of complex light curves of tumbling or binary objects difficult. During the oppositions, when they are away from the Galactic plane, such as in January 2024, the asteroids are fainter (V magnitude of 21 or more, even for the primary).

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References

Bottke, W. F., Nolan, M. C., Greenberg, R., & Kolvoord, R. A. 1994, Icarus, 107, 255
Bottke, W. F., Vokrouhlický, D., Rubincam, D. P., & Nesvorný, D. 2006, Ann. Rev. Earth Planet. Sci., 34, 157
Bottke, W. F., Vokrouhlický, D., Ballouz, R. L., et al. 2020, AJ, 160, 14
Duncan, M. J., Levison, H. F., & Lee, M. H. 1998, AJ, 116, 2067
Farnocchia, D., Chesley, S. R., Vokrouhlický, D., et al. 2013, Icarus, 224, 1
Fatka, P., Moskovitz, N. A., Pravec, P., et al. 2022, MNRAS, 510, 6033
Gray, B. 2022, Astrophysics Source Code Library [record ascl:`2202.016`]
Greenberg, R. 1982, AJ, 87, 184
Jewitt, D., Hsieh, H., & Agarwal, J. 2015, in Asteroids IV, eds. P. Michel, F. E. DeMeo, & W. F. Bottke, 221
Jewitt, D., Kim, Y., Luu, J., et al. 2019, ApJ, 876, L19
Kyrylenko, I., Krugly, Y. N., & Golubov, O. 2021, A&A, 655, A14
Margot, J. L., Pravec, P., Taylor, P., Carry, B., & Jacobson, S. 2015, in Asteroids IV, eds. P. Michel, F. E. DeMeo, & W. F. Bottke, 355
Park, R. S., Folkner, W. M., Williams, J. G., & Boggs, D. H. 2021, AJ, 161, 105
Pravec, P., Vokrouhlický, D., Polishook, D., et al. 2010, Nature, 466, 1085
Pravec, P., Fatka, P., Vokrouhlický, D., et al. 2019, Icarus, 333, 429
Vokrouhlický, D., & Nesvorný, D. 2008, AJ, 136, 280
Vokrouhlický, D., & Nesvorný, D. 2009, AJ, 137, 111
Vokrouhlický, D., Bottke, W. F., Chesley, S. R., Scheeres, D. J., & Statler, T. S. 2015, in Asteroids IV, eds. P. Michel, F. E. Demeo, & W. F. Bottke, 509
Ye, Q., Kelley, M. S. P., Bodewits, D., et al. 2019, ApJ, 874, L16
Žižka, J., Galád, A., Vokrouhlický, D., et al. 2016, A&A, 595, A20

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[3] In a more detailed effort, we would need to consider a large number of heliocentric positions and velocities of the primary along its nominal orbit in the past. Then we would need to create synthetic clones of the secondary at these epochs, and propagate the orbits forward in time to the epoch of the recent encounter. We approximated the results from such an extensive approach by a simpler integration backward in time.

Appendix A: Remeasured and new observations of (458271) 2010 UM26 and 2010 RN221

In this section, we provide information about new astrometric data for (458271) 2010 UM26 and 2010 RN221 that was not previously available at the MPC repository. The sample includes some data from archival frames, in which we remeasured the positions of the two objects with greater care, and also our new observations taken in summer 2022 (Sec. 2).

Table A.1. Astrometry of (458271) 2010 UM26 and 2010 RN221 extracted during this work, with the corresponding formal error bars in both coordinates. The observing site is denoted using its MPC code (third column).

Asteroid		MPC code	Date (UTC)	α (°)	δ (°)	$\Delta\alpha$ (″)	$\Delta\delta$ (″)
458271	2010 UM26	568	2005-05-14T09:05:44.0	226.661558	-18.009950	0.046	0.037
458271	2010 UM26	568	2005-05-14T09:54:18.0	226.652996	-18.007039	0.047	0.038
458271	2010 UM26	568	2005-05-14T10:50:15.7	226.643133	-18.003653	0.051	0.044
458271	2010 UM26	Z84	2022-05-28T01:01:05.2	293.733730	-17.747669	0.25	0.25
458271	2010 UM26	Z84	2022-05-30T02:07:33.7	293.765217	-17.632078	0.7	0.7
458271	2010 UM26	Z84	2022-06-24T22:51:07.3	291.382840	-16.531971	0.23	0.22
458271	2010 UM26	Z84	2022-06-25T00:12:06.4	291.371840	-16.530500	0.17	0.17
458271	2010 UM26	Z84	2022-06-25T01:33:01.8	291.360718	-16.529012	0.17	0.12
458271	2010 UM26	Z84	2022-06-25T02:50:25.7	291.350087	-16.527466	0.19	0.21
458271	2010 UM26	Z84	2022-07-07T21:22:32.2	288.565779	-16.277297	0.2	0.2
458271	2010 UM26	Z84	2022-07-08T21:56:06.8	288.317946	-16.265668	0.18	0.21
458271	2010 UM26	Z84	2022-07-09T00:08:40.2	288.294552	-16.264795	0.13	0.12
458271	2010 UM26	Z84	2022-07-09T02:21:10.5	288.271131	-16.263635	0.27	0.21
	2010 RN221	568	2005-05-14T09:05:44.0	226.661012	-18.009844	0.068	0.063
	2010 RN221	568	2005-05-14T09:54:18.0	226.652492	-18.006931	0.077	0.072
	2010 RN221	568	2005-05-14T10:50:15.7	226.642671	-18.003558	0.09	0.086
	2010 RN221	G96	2006-12-13T07:52:33.6	78.082754	+20.140317	0.51	0.51
	2010 RN221	G96	2006-12-13T08:17:11.0	78.077912	+20.139436	0.27	0.27
	2010 RN221	Z84	2022-05-30T02:03:46.2	293.754788	-17.634214	0.24	0.25
	2010 RN221	Z84	2022-06-25T01:13:01.3	291.350595	-16.531642	0.34	0.34
	2010 RN221	Z84	2022-07-09T02:21:10.5	288.257447	-16.266148	0.26	0.24