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THE COMMON ROOTS OF ASTEROIDS (6070) RHEINLAND AND (54827) 2001 NQ8

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ABSTRACT

Our previous analysis of the available catalogues of asteroid orbits revealed the existence of pairs of bodies residing on nearby trajectories. Their proximity, far tighter than one would expect from random fluctuations of the distribution in the orbital space, implies that some process(es) disintegrated a common precursor of asteroids in each pair some thousands to hundreds of thousands of years ago. The analysis of these process(es) is of great interest in planetary science. Here we focus on the best characterized paired asteroids—(6070) Rheinland and (54827) 2001 NQ8—and determine conditions of their separation in the past. First, by using a numerical model that ignores asteroids' gravity, we show there is a possibility of an approach closer than 1000 km (radius of their Hill sphere) 17.22 ± 0.28 kyr ago; we interpret this as the origin of the pair. This is the most accurate determination of an asteroid age so far. We also find that the median encounter velocity at infinity is 17 cm s^{-1}, while its component normal to the orbit of larger asteroid (6070) Rheinland is only 21 mm s^{-1}. Second, we model the initial phase of separation of these two bodies by including the effects of mutual gravitational interaction when their distance is smaller than the Hill radius. Our simulations indicate their minimum initial separation may have been comparable to the physical distance of their centers. This is the first time an accurate numerical integration can bring two asteroid fragments into a single point in the past. Resting geometry (when 2001 NQ8 touches Rheinland), close- and distant-satellite initial configurations are all possible, but cannot be discriminated so far.

Key words: minor planets, asteroids

1. INTRODUCTION

Expanding on numerous suggestions in 1990s (e.g., Drummond 1991, 1998), the existence of a significant population of small main-belt asteroids residing on closely resembling orbits was established by Vokrouhlický & Nesvorný (2008, hereafter VN08). This is mainly because all-sky surveys enabled the discovery of an impressive number of small bodies in the main belt over the past years. VN08 suggested that the two asteroids in each pair originated from a common parent object. An a priori unknown process (or processes) made the parent body catastrophically disintegrate thousands to hundreds of thousands of years ago. Obviously, the analysis of such process or processes is of high importance for studies of small bodies, mainly because they imply that the small asteroid population evolves on surprisingly short timescales.

The ultimate goal one may seek is to obtain a reconstruction of the initial configuration of the two asteroids as close to the split event as possible. Note that this ideal goal has never been achieved for any of the known asteroid families (e.g., Nesvorný et al. 2006; Nesvorný & Vokrouhlický 2006), but the potential youth of the pairs may suggest it could possibly be accomplished here. VN08 made the first step toward this goal by performing backward integrations of the known pairs of asteroids. They noticed that in most cases the orbital and force-model uncertainties prevent an unambiguous determination of the formation of the pairs. A fortuitous exception is the pair of asteroids (6070) Rheinland and (54827) 2001 NQ8 for which they determined a putative origin 16.5–19 kyr ago.

The purpose of this paper is to perform an improved analysis of the possible past history of this asteroid pair. At first, we repeat the VN08 analysis (i) with more orbital clones and denser time resolution, and (ii) using improved initial orbits (by adding available astrometry from the 2008 opposition; Section 3). In addition, we also include the effects of mutual gravitational interaction of the two asteroids during their close encounter (Section 4). This allows us to investigate the behavior of the two components in the pair during their initial separation (Section 5).

2. (6070) RHEINLAND AND (54827) 2001 NQ8 PAIR

This pair of asteroids resides at the outskirts of the Nysa-Polana clan in the inner part of the main belt, with moderately large eccentricity and small inclination. The osculating orbital elements used as initial conditions for the numerical integration in this study are given in Table 1. The relative uncertainty of each element is $\sim 10^{-7}$ or better due to numerous observations covering long orbital arcs (52 and 16 yr, respectively). The small separation of the semimajor axis values for Rheinland and 2001 NQ8 ($\sim 10^{-3}$ AU) is produced by a slightly different phase of their oscillation due to planetary perturbations. The nonidentical past evolution of semimajor axes of the two asteroids also contributed to the accumulation of the $\simeq 36^\circ$ difference in mean longitude values. The fact that these two orbits are actually much closer to each other than would be first guessed from the osculating orbital elements is, for example, revealed by their proper element values. The proper orbital elements (a_P, e_P, $\sin i_P$) differ by $\delta a_P / a_P \simeq 2 \times 10^{-5}$, $\delta e_P \simeq 10^{-5}$, and $\delta \sin i_P \simeq 4 \times 10^{-6}$, at the accuracy level with which these elements could be computed (e.g., Knežević et al. 2002 and http://newton.dm.unipi.it/). In other words, the two orbits have identical proper elements within the statistical uncertainty.

Until recently, there was no spectroscopic information about the asteroids in this pair except that broadband observation by Sloan Digital Sky Survey (SDSS) suggested Rheinland may be an S-type asteroid (we used data in the ADR3 catalog; e.g., Ivezić et al. 2001). The value of the first two principal components of its spectrum, estimated from SDSS observation, $PC_1 = 0.43 \pm 0.05$ and $PC_2 = -0.24 \pm 0.05$, places (6070) Rheinland within the broad S complex (e.g., Bus & Binzel 2002).

Table 1
Osculating Orbital Elements, Their Uncertainties, and Other Parameters of the Asteroid Pair (6070) Rheinland and (54827) 2001 NQ8

Asteroid		a (AU)	h	k	p	q	λ (deg)	H (mag)
6070	Rheinland	2.386956193	0.06077340	0.202026878	0.027191597	0.002849215	231.753484	13.6
54827	2001 NQ8	2.387807377	0.06013197	0.20223405	0.027181413	0.00284362	267.288577	15.7
Uncertainty		δa	δh	δk	δp	δq	$\delta\lambda$	
6070	Rheinland	3.3e-8	1.0e-7	9.4e-8	8.2e-8	8.5e-8	1.4e-5	...
54827	2001 NQ8	6.9e-8	1.2e-7	1.8e-7	9.9e-8	1.5e-7	2.1e-5	...

Notes. Osculating orbital elements and their uncertainty are given for epoch MJD 54600 provided by the `OrbFit9` software (http://newton.dm.unipi.it/orbfit/). We use heliocentric equinoctial system of nonsingular elements: a is the semimajor axis, $(h, k) = e(\sin\varpi, \cos\varpi)$ where e is the eccentricity and ϖ is the longitude of perihelion, $(p, q) = \tan(i/2)(\sin\Omega, \cos\Omega)$, where i is the inclination and Ω is the longitude of node, and $\lambda = \varpi + M$ is the mean longitude in orbit (M is the mean anomaly). Default reference system is that of mean ecliptic of J2000. The adopted absolute magnitude values are given by the MPC. We use $p_V = 0.3$ geometric albedo to derive the $D \simeq 4.62$ km and $D \simeq 1.76$ km size for (6070) Rheinland and (54827) 2001 NQ8. These are very likely underestimates of their real size, especially for (54827) 2001 NQ8, for which other sources (such as AstDyS node at Pisa) give smaller H value of 15.2.

This was expected given Rheinland's location in the inner part of the main belt. Vernazza et al. (2008) reported results of their recent spectroscopic observations of Rheinland and 2001 NQ8 and concluded that (6070) Rheinland is an Sq-type and (54827) 2001 NQ8 is a Q-type asteroid. This observation, together with data for asteroids in very young families (e.g., Mothé-Diniz & Nesvorný 2008; Vernazza et al. 2008), supports an extremely young age of this pair.

The absolute magnitude values H adopted in Table 1 are from the minor planet center (MPC) database. Because elongated objects have frequently lightcurve amplitude of 0.5–0.6 mag, and because of the possible systematic effects in surveys, we can only assume these values are ± 0.5 mag accurate. Indeed, the independent `OrbFit9` software at Pisa University currently gives an absolute magnitude of $H \simeq 15.2$ for (54827) 2001 NQ8 (while about the same value as the MPC for (6070) Rheinland). The size/mass estimate is important for our analysis because it affects the strength of the Yarkovsky forces acting on both the asteroids. To make sure that our analysis covers the actual values we tend to maximize the Yarkovsky effects by adopting the larger H value for (54827) 2001 NQ8 (from the MPC node), and we also adopt rather large value of the geometric albedo $p_V = 0.3$ when converting H to size D of the two asteroids. With that conservative approach, we obtain $D \simeq 4.62$ km for (6070) Rheinland and $D \simeq 1.76$ km for (54827) 2001 NQ8.

To date, we have no information about the rotation state of the two asteroids and their surface thermal properties. This makes Yarkovsky forces on the two bodies unconstrained such that our analysis has to span all admissible values for bodies of their estimated size.

3. PRE-ENCOUNTER DYNAMICS

The first step of our effort is directed toward constraining the age of the pair. Similar to the work of VN08 this is done by backward propagation of the orbits until the two asteroids get into a close encounter. At this step, the closeness we require is not marked by the estimated physical size of the two bodies but rather the radius of a Hill sphere characterizing strength of their mutual gravitational integration (see Section 4). This permits us to ignore the mutual gravitational interaction of the two bodies in this section. For the pair studied here this critical distance is $\simeq 1000$ km.

We used the symplectic integrator `SWIFT_MVS` (e.g., Levison & Duncan 1994) and 3.65 day timestep. Gravitational perturbations due to all planets, except for Mercury, were taken into account; their masses and initial state vectors at the MJD 54600 epoch were obtained from JPL DE405 ephemerides. We also included dynamical effects of nonconservative Yarkovsky forces on the two asteroids in our analysis. For that purpose, we modified the original code in a way similar to that of Brož (2006). In order to simplify our work, and also due to the lack of more accurate information, we replaced the full formulation of the Yarkovsky forces with an along-track acceleration $\frac{1}{2}n(na/v)(da/dt)$, with n the orbital mean motion, a the orbital semimajor axis, and v the instantaneous orbital velocity. Such a perturbative acceleration produces the same averaged semimajor axis drift da/dt as expected from the theory of the Yarkovsky effect. With that, we only span the admissible da/dt values and do not need to link them to detailed thermal parameters of the Yarkovsky forces. For a reference, the maximum expected value for a kilometer-sized asteroid at $a = 2.5$ AU is $(da/dt)_{\max} \simeq 3 \times 10^{-4}$ AU My^{-1} (e.g., Bottke et al. 2002, 2006). This value is adopted in our code and scaled using: (i) $\propto 1/D$ for objects of different size D and (ii) $\propto 1/a^2$ for orbits at a different semimajor axis a.

The possibility of reconstructing the past configuration of the two asteroids faces two fundamental obstacles: (i) uncertainty due to inaccurate knowledge of the current orbital parameters of the pair and (ii) uncertainty due to unconstrained physical parameters of the force model (namely the Yarkovsky forces). Assuming an age less than 50 kyr for this pair, the first issue is not unsurmountable because the numerically determined Lyapunov timescale for orbits of Rheinland and 2001 NQ8 is about 55 kyr (e.g., http://newton.dm.unipi.it/). So, the expansion of the original uncertainty ellipsoid should not be substantial over a shorter timescale; yet, even the linear growth may extend the extreme realizations of the initial orbits far in the along-track direction. A naive estimate would give $\delta R \sim 3\pi(T/P)\delta a$ along-track difference after time T elapsed (P is the orbital period and δa the initial semimajor axis uncertainty). In $T \simeq 17$ kyr, one obtains $\delta R \sim 10^5$ km, far larger than the sought approach distance of the two asteroids. Similarly, the future/past evolution of different realizations of the Yarkovsky effect may spread over mean longitude in orbit interval $\delta\lambda/2\pi \sim \frac{3}{2}((da/dt)_{\max}/a)(T^2/P)$, where $(da/dt)_{\max}$ is the estimated maximum drift due to the Yarkovsky forces (e.g., Vokrouhlický 1999; Vokrouhlický et al. 2000). In $T \simeq 17$ kyr, $\delta\lambda$ may grow to nearly 20° for 2001 NQ8.

Because all orbital realizations that start within the current uncertainty interval are statistically identical, and because we do not have any a priori information about the strength and direction of the Yarkovsky forces, we have to consider numerous past evolutions of (6070) Rheinland and (54827) 2001 NQ8. In this respect we use 31 clones that randomly sample the uncertainty ellipsoid of the initial data in equinoctial coordinates (Table 1) and we assign to each of them 51 possible values of the Yarkovsky force. For the latter we uniformly sample the estimated interval of the semimajor axis drift values $[-(da/dt)_{\rm max}, (da/dt)_{\rm max}]$. This makes altogether 1581 clones of each of the two asteroids. We first propagate orbits of each of them for 100 kyr to the past with 10 yr sampling of the asteroid positions, but upon verifying results of VN08, namely locating a deep minimum in mutual distance of the two asteroids in between 16.5 and 19 kyr, we focus on the interval 16–20 kyr ago and scan the orbital configurations with a 0.1 yr sampling.

With that done, we obtained positions of the asteroid clones at a dense time grid during the time interval of interest in the past. At each timestep, we then randomly chose 5×10^5 different clone combinations and determined their mutual distance in Cartesian space. We recorded those combinations for which the distance was less than twice the estimated Hill radius ($\simeq$ 1000 km; Section 4), and we used them in the second step of our analysis described in the next section.

4. ENCOUNTER DYNAMICS

When the two asteroids approach at close distance our previous propagation scheme that does not take into account their mutual gravitational interaction is no more valid. We must therefore extend our model to consider the asteroid–asteroid interaction effects. In a complete approach we would need to consider the two asteroids as extended bodies of an irregular shape and decompose their motion into translational and rotational components. Gravitational potential energy $U(\mathbf{r}; A_1, A_2)$ would depend on both relative position vector $\mathbf{r}$ of their centers-of-mass and rotation matrices A_1 and A_2 characterizing orientation of their body-fixed frames (e.g., Maciejewski 1995; Werner & Scheeres 2005). Without any constrains on the rotation state and the shape of (6070) Rheinland and (54827) 2001 NQ8 we refrain from such a detailed modeling in this study and consider translational part of the problem only.

The encounter dynamics is best described by Jacobi-type variables instead of the heliocentric position vectors and velocities used in Section 3. This is represented with a linear transformation $(\mathbf{r}_1, \mathbf{r}_2) \rightarrow (\mathbf{r}, \mathbf{R})$ such that $\mathbf{r}_1 = \mathbf{R} - X_2\mathbf{r}$ and $\mathbf{r}_2 = \mathbf{R} + X_1\mathbf{r}$. Here, $(\mathbf{r}_1, \mathbf{r}_2)$ are the heliocentric position vectors of the two asteroids, $\mathbf{r}$ is the relative position vector of the second asteroid with respect to the first asteroid (more accurately their centers-of-mass), and $\mathbf{R}$ is the heliocentric position vector of the center-of-mass of the asteroid pair. Denoting their masses by m_1 and m_2, we also introduce $X_1 = m_1/(m_1 + m_2)$ and $X_2 = m_2/(m_1 + m_2)$, notably their fractional contribution to the total mass of the pair.

With the interaction potential $V = U/m_r$ of the pair, namely mutual potential energy U divided by the reduced mass $m_r = m_1 m_2/(m_1 + m_2)$, the equations of translational motion read

$$\frac{d^2\mathbf{r}}{dt^2} + \frac{\partial V}{\partial \mathbf{r}} + \mu'\left(\frac{\mathbf{r}_2}{r_2^3} - \frac{\mathbf{r}_1}{r_1^3}\right) = 0, \quad (1)$$

$$\frac{d^2\mathbf{R}}{dt^2} + (\mu + \mu')\left(X_1\frac{\mathbf{r}_1}{r_1^3} + X_2\frac{\mathbf{r}_2}{r_2^3}\right) = 0, \quad (2)$$

where $\mu = G(m_1 + m_2)$ and $\mu' = Gm_0$ (m_0 is the solar mass). We neglect planetary perturbations here. Our estimate in the Appendix indicates this is well justified by the fact that the encounter phase lasts typically 100–300 days, short enough to prevent the accumulation of planetary effects into significant perturbation. We also note the asteroid gravitational coupling to the Sun (contributing to Equation (2)) is assumed to be point-like, and only their mutual interaction may eventually require more complex description by a potential V.

Assuming the point-mass approximation for the mutual gravitational interaction of the two asteroid components in the pair we have $V = -\mu/r$. Moreover, we note that the solar tidal field, expressed by the last terms in the left-hand sides of Equations (1) and (2), has significantly more important influence on the relative motion of the two asteroids than on the heliocentric motion of their center-of-mass. We can thus easily restrict the acceleration in Equation (2) to its quadrupole-level expression. We finally obtain

$$\frac{d^2\mathbf{r}}{dt^2} + \frac{\mu}{r^3}\mathbf{r} = -\mu'\left(\frac{\mathbf{r}_2}{r_2^3} - \frac{\mathbf{r}_1}{r_1^3}\right), \quad (3)$$

$$\frac{d^2\mathbf{R}}{dt^2} + \frac{\mu' + \mu}{R^3}\mathbf{R} = 3X_1X_2\frac{\mu' + \mu}{R^3}\alpha\left[c\mathbf{r} - \frac{1}{2}\alpha(5c^2 - 1)\mathbf{R}\right], \quad (4)$$

where $\alpha = r/R$ and $c = \mathbf{r} \cdot \mathbf{R}/(rR)$ is a directional cosine of the unit directions defined by position vectors $\mathbf{r}$ and $\mathbf{R}$. In fact, dropping the right-hand side in Equation (4) would also be an acceptable approximation[3]; this would imply that $\mathbf{R}$ moves along an arc of Keplerian ellipse during the encounter phase. Because we start our encounter simulation at a sufficiently large distance of the two asteroids, we cannot a priori restrict right-hand side of Equation (3) to its quadrupole level. We thus always keep the complete form in our model. It is nevertheless instructive to briefly discuss the quadrupole approximation

$$-\mu'\left(\frac{\mathbf{r}_2}{r_2^3} - \frac{\mathbf{r}_1}{r_1^3}\right) \simeq -\frac{\mu'}{R^3}(\mathbf{r} - 3\,\alpha c\mathbf{R}). \quad (5)$$

This formula readily provides an estimate of the asteroid distance at which we must replace the pre-encounter to the encounter description of our problem. We note that the mutual gravitational attraction of the two asteroids, expressed by the second term in Equation (3), equals in magnitude the solar tide (Equation (5)) when $r = r_{\rm e}$ with

$$r_{\rm e} = R\left(\frac{\mu}{2\mu'}\right)^{1/3}. \quad (6)$$

This is only $\simeq$ 14% larger value than the conventionally used Hill distance, $r_{\rm Hill}$, where

$$r_{\rm Hill} = R\left(\frac{\mu}{3\mu'}\right)^{1/3}. \quad (7)$$

Both $r_{\rm e}$ and/or $r_{\rm Hill}$ delimit the zone inside which the mutual gravitational effects of the two asteroids must be taken into account.

[3] Note that a very rough estimate of a displacement δR due to its effect can be given by $\delta R \sim \alpha^2 ae$, where a and e are semimajor axis and eccentricity of the heliocentric orbit. For the Rheinland and 2001 NQ8 pair we thus obtain $\delta R \lesssim$ 1–10 m, significantly smaller than the displacements due to neglected dynamical effects (see the Appendix).

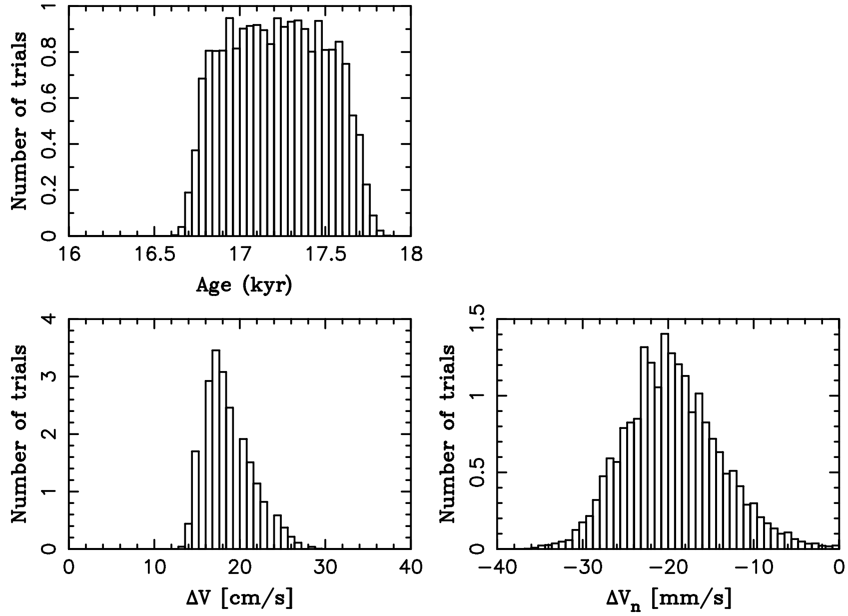

Figure 1. Statistical properties of the backward-integrated clones of asteroids (6070) Rheinland and (54827) 2001 NQ8. We selected pairs of clones that approached closer than $r_{\rm Hill} \simeq 1015$ km; number of trials on the ordinates should be multiplied by 10,000 (normalized here for clarity). Top: distribution of time instants of the approach that marks the age of the pair. The mean value and formal standard deviation are 17.22 ± 0.28 kyr (the realistic uncertainty might be slightly larger due to non-Gaussian distribution). Bottom and left: distribution of the relative velocity Δv at encounter. Bottom and right: distribution of the relative velocity component Δv_n normal to the heliocentric orbital plane of (6070) Rheinland. The fact that $\Delta v_n/\Delta v \leqslant 0.13$ suggests that the orbital planes of the two asteroids were nearly identical at the encounter and their separation occurs in their heliocentric orbital plane. The ordinates are arbitrary and derive from the number of clones used, time sampling of the output, and the number of identification trials at each time. In total, we used $\simeq 210,000$ solutions.

Equations (3) and (4) were numerically integrated using a high-accuracy Burlish–Stoer scheme with variable timestep (e.g., Press et al. 1999). The initial conditions for these integrations were obtained from Section 3. We used only the pairs of clones that approached at the $2r_{\rm Hill}$ distance (to be conservative enough). Each of these cases was propagated to the instant of the closest approach of the two bodies.

5. RESULTS

In this section, we apply the two-step methodology from Sections 3 and 4 to the case of (6070) Rheinland and (54827) 2001 NQ8 pair of asteroids.

Pre-encounter dynamics. Figure 1 (top) shows statistical distribution of time instants in the past when two possible clones get closer than $r_{\rm Hill}$. Given the number of clones used, time sampling of the integration output, and the number of identification trials we note there are 210,000 such solutions that contribute to the mean time value of 17.22 kyr with a standard deviation of 0.28 kyr. Because the distribution is not exactly Gaussian, the realistic uncertainty in the age determination might be slightly larger.[4] The bottom panels of Figure 1 indicate that the two asteroids approach each other very gently and nearly in the heliocentric orbital plane of (6070) Rheinland (taken for reference here). In particular, the total relative encounter velocity Δv at the Hill sphere distance has a median value 17 cm s^{-1}. Strikingly, the component Δv_n perpendicular to the orbital plane of Rheinland has a median value of only 21 mm s^{-1}.

Similar to results in VN08 (see their Figure 7) we confirm there is no other significant past close encounter of these two orbits until $\simeq$ 50 kyr. Beyond this limit, both geometrical and Yarkovsky clones spread over the whole extent of mean longitude values and no deterministic work is possible. Applying Occam's razor, we interpret the 17.22 kyr encounter as the time when Rheinland and 2001 NQ8 separated from their common ancestor.

Encounter dynamics. All 210,000 pair/clone solutions that approached at a distance less than $r_{\rm Hill}$ may serve as starting conditions for numerical reconstruction of the encounter configuration. Given the level of uncertainty of the model, which stems from many unknown parameters including the rotation state, shape, and exact mass of the two bodies, we selected only the first 1000 trials for which the previously determined orbits approached the closest. We used their heliocentric state vectors at $2r_{\rm Hill}$ mutual distance as initial conditions to demonstrate a variety of possible encounter configurations.

Some initial data for the encounter solutions had nearly zero angular momentum and they lead to configurations with a minimum distance of the two asteroids well below their physical size, thus bringing them virtually to a single point in space.[5] Figure 2 shows a less extreme case when the two bodies just touch at their minimum separation distance. Their relative velocity at that moment increased to $\sim$1.7 m s^{-1}, as a compensation of decreasing mutual potential energy. This is comparable, or even smaller, to the circumferential velocity of Rheinland-sized body rotating close to the fission limit. Figures 3 and 4 show encounter configurations for which the minimum distance geometry might correspond to close and/or more distant satellite system with separations typical from the observations of the near-Earth and main-belt

4 Note though that a box-like distribution has a standard deviation equal to the half-width of the box.

5 Note that the mentioned minuscule encounter velocity at $2r_{\rm Hill}$ mutual distance compared to the escape velocity from the estimated parent object implies a strong focusing effect. This means that orbits with impact parameters up to several tens of Rheinland's radius can still result in mutual impact of the two asteroids.

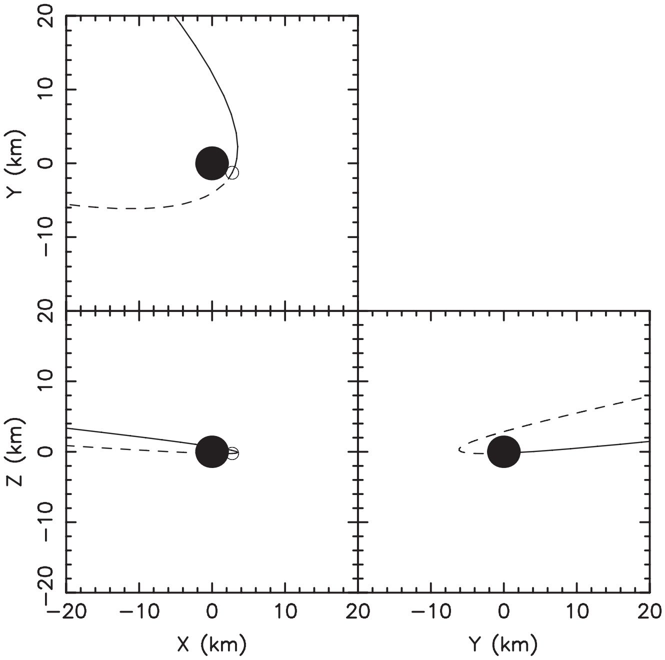

Figure 2. Numerically reconstructed encounter of (6070) Rheinland (solid circle) and (54827) 2001 NQ8 (open circle): the three panels show the projection of the orbit onto three planes (X, Y), (X, Z), and (Y, Z). The unit vectors $(\mathbf{e}_X, \mathbf{e}_Y, \mathbf{e}_Z)$ are given by radial $\mathbf{e}_X = \mathbf{R}/R$, transverse $\mathbf{e}_Y = (d\mathbf{R}/dt - \sigma\mathbf{R})/\sqrt{1-\sigma^2}$ (with $\sigma = \mathbf{R} \cdot d\mathbf{R}/dt$), and normal $\mathbf{e}_Z = \mathbf{e}_X \times \mathbf{e}_Y$ directions determined by the heliocentric center-of-mass state vector $(\mathbf{R}, d\mathbf{R}/dt)$ when $r = 2r_{\rm Hill}$ (initial data of the encounter phase of our numerical model; Section 4). In this case, the asteroids in the pair touch at their closest approach. The solid line denotes the separation orbit, while the dashed line is just a numerical continuation of this solution to the past.

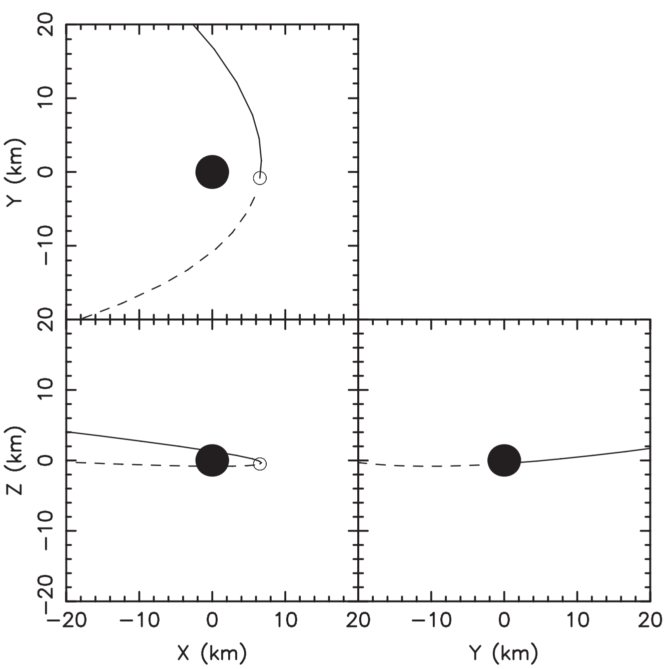

Figure 3. The same as in Figure 2. In this case though, the minimum distance of the two orbits is ~ 6.6 km, namely ~ 2.9 radii of (6070) Rheinland.

binaries (e.g., Pravec & Harris 2007; Pravec et al. 2007; http://www.asu.cas.cz/~asteroid/binastdata.htm).

Obviously, in both cases—resting and/or satellite configurations—the detailed mechanism of the onset of the

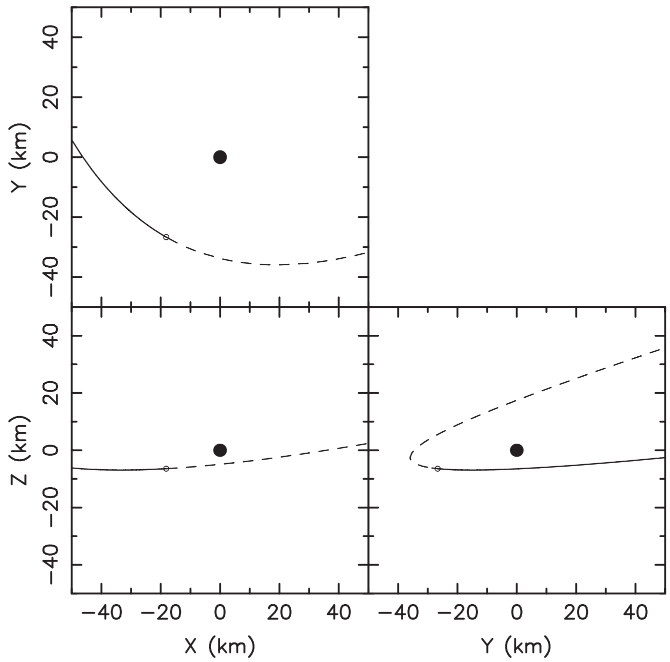

Figure 4. The same as in Figure 2. In this case though, the minimum distance of the two orbits is ~ 32.6 km, namely ~ 14.1 radii of (6070) Rheinland.

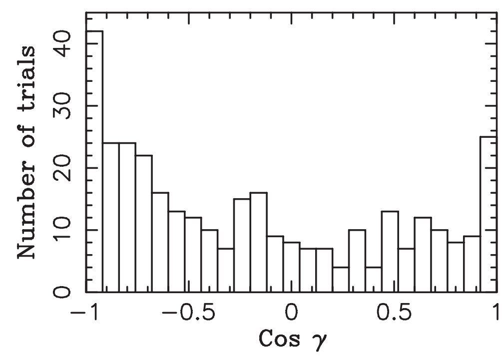

Figure 5. Distribution of $\cos\gamma$ values for those of the 1000 integrated encounter solutions that lead to an approach at distance between 1 and 15 radii of (6070) Rheinland (solid histogram); γ denotes the angle between center-of-mass angular momentum $\mathbf{R} \times \mathbf{V}$ and the angular momentum of the relative motion $\mathbf{r} \times \mathbf{v}$ at the minimum separation of the two asteroids.

instability between the two components is yet to be studied. Our work only shows that configurations similar to believable initial states (fissioned primary and/or satellites system undergoing instability) are within the reach of past histories of Rheinland and 2001 NQ8 pair as reconstructed by backward orbital propagation. Unfortunately, we have not seen any statistical preference to one or the other configuration in the currently available data. Therefore, different scenarios for the origin of the Rheinland and 2001 NQ8 pair cannot be discriminated by this work.

To dwell little more beyond the general conclusions above, we next investigate possible implications of the most significant feature of the initial data at the Hill-sphere separation, namely the $\Delta v_n/\Delta v \leqslant 0.13$ fractional contribution of Δv_n velocity normal to the orbital plane of (6070) Rheinland in the total relative velocity Δv. Does this mean the two asteroids must encounter in the $(\mathbf{R}, \mathbf{V})$ plane close to that of (6070) Rheinland? Results in Figure 5 indicate this is not really true: the small Δv_n relative velocity component can still mean that in particular solutions, the asteroid 2001 NQ8 may encounter Rheinland in the direction normal to its orbital plane about the Sun. More precisely, let us define an angle γ between the total angular momentum $\mathbf{R} \times \mathbf{V}$ of the center-of-mass motion and $\mathbf{r} \times \mathbf{v}$ characterizing the relative motion of the two asteroids. While the former approximately conserves (Equation (4)), the latter evolves due to the interaction with solar tides (Equation (3)). Figure 5 shows the distribution of $\cos\gamma$ at the moment of the closest encounter for the 1000 propagated cases, where we however discarded all solutions for which the minimum encounter distance was larger than 15 radii of Rheinland. We note a slight statistical preference to values near $\cos\gamma \simeq -1$ which would ultimately require the parent body of the pair, and likely the asteroid (6070) Rheinland, was a retrograde rotator. This hypothesis is directly testable by the analysis of the rotational lightcurves of (6070) Rheinland.

6. CONCLUSIONS

Studies of past orbital history of asteroids in the pairs discovered by VN08 could potentially provide important information about the processes that lead to their origin (see VN08 for further details). Here, we have demonstrated this possibility in the case of (6070) Rheinland and (54827) 2001 NQ8 pair. We found that the plausible initial configurations reproduce those from theoretical models (direct fission and/or satellite instability), but current uncertainties prevent us from determining which one is the more likely.

Astronomical observations of different nature are needed to help constrain the variety of unknown parameters that prevent both (i) refined work in the case of the pair studied in this paper, and (ii) preliminary age determination in the case of all other paired objects. These observations include (i) further astrometry that would tighten the uncertainty ellipsoid of the initial data for numerical integrations and (ii) optical lightcurve and thermal observations that would eventually constrain parameters of the Yarkovsky forces and size estimation, and provide information about the shape of the two asteroids.

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APPENDIX

ADDITIONAL PERTURBING TERMS IN THE ENCOUNTER DYNAMICS

We briefly overview a more complete form of the dynamical equations needed to describe the asteroid encounter at higher accuracy. Apart from the mutual gravitational interaction and the solar tide effects, used in Section 4, additional perturbing forces should be potentially considered.

First, planetary perturbations represent a logical addendum to the previous model. Assume N planets in the system with heliocentric position vectors $\mathbf{r}_i$ ($i = 1, 2, \ldots, N$). Because our asteroid pair has negligible effect on their dynamics, the planetary motion is given by a standard N-body problem. The encounter of the asteroid pair is described by the Jacobi-type vectors $(\mathbf{r}, \mathbf{R})$ as in Section 4 that now satisfy a generalized system of equations

$$\frac{d^2\mathbf{r}}{dt^2} + \frac{\partial V}{\partial \mathbf{r}} + \mu' \left(\frac{\mathbf{r}_2}{r_2^3} - \frac{\mathbf{r}_1}{r_1^3} \right) = \sum_{i=1}^{N} \mu_i \left(\frac{\boldsymbol{\Delta}_{i2}}{\Delta_{i2}^3} - \frac{\boldsymbol{\Delta}_{i1}}{\Delta_{i1}^3} \right), \qquad \text{(A1)}$$

$$\frac{d^2\mathbf{R}}{dt^2} + (\mu + \mu') \left(X_1 \frac{\mathbf{r}_1}{r_1^3} + X_2 \frac{\mathbf{r}_2}{r_2^3} \right) = \sum_{i=1}^{N} \mu_i \left(X_1 \frac{\boldsymbol{\Delta}_{i1}}{\Delta_{i1}^3} + X_2 \frac{\boldsymbol{\Delta}_{i2}}{\Delta_{i2}^3} - \frac{\mathbf{r}_i}{r_i^3} \right), \qquad \text{(A2)}$$

where $\boldsymbol{\Delta}_{i1} = \mathbf{r}_i - \mathbf{r}_1$ and $\boldsymbol{\Delta}_{i2} = \mathbf{r}_i - \mathbf{r}_2$ are relative position vectors of the ith planet with respect to the first and second asteroid in the pair, and $\mu_i = Gm_i$ (m_i is the mass of ith planet); $\mathbf{r}_i$ are assumed to be known functions of time in Equations (A1) and (A2). A very rough estimate of a maximum displacement δr due to Jupiter can be obtained using the quadrupole approximation (Equation (5)) of this planet's field. Assuming a constant orientation near conjunction with Jupiter we have $\delta r \sim 0.15$ km or smaller during the encounter phase of motion (timescale of $\simeq 100$ days).

Second, we may note that the form of Equations (A1) and (A2) hints the way of further generalizations. Assume there are additional perturbing accelerations $\mathbf{a}_1$ and $\mathbf{a}_2$ applied on the first and the second asteroid of the pair. We may, for example, include radiation-born accelerations such as direct radiation pressure or recoil effects of the thermally re-radiated sunlight (so-called Yarkovsky effect; e.g., Vokrouhlický & Milani 2000; Vokrouhlický et al. 2000; Bottke et al. 2002, 2006). Then, additional accelerations have to be considered: (i) $\mathbf{a}_2 - \mathbf{a}_1$ in the right-hand side of Equation (A1), and (ii) $X_1\mathbf{a}_1 + X_2\mathbf{a}_2$ in the right-hand side of Equation (A2) (see also Vokrouhlický et al. 2005, where this model has been applied to the dynamics of binary asteroids). We can again give a very rough estimate of a maximum expected displacement δr due to the radiative effects; assuming a constant force that is unrealistically large, we obtain $\delta r \sim 0.1$ km or smaller for kilometer-sized asteroids during the encounter phase of motion.

Third, we recall that the mutual interaction potential $V(\mathbf{r}; A_1, A_2)$ depends not only on the relative vector $\mathbf{r}$ of the asteroids center-of-mass, but also on attitude matrices A_1 and A_2 that characterize transformation between the inertial system and system of their body-fixed axes. Equations (A1) and (A2), which describe the translational part of the motion, have to be thus completed with Euler-type equations describing the rotational part of the motion. Formulation of this problem has been considered in many sources including Maciejewski (1995) or Werner & Scheeres (2005); the latter reference also gives an efficient scheme to compute the interaction potential V for two bodies of an arbitrary shape. We refer interested readers to these sources.

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