Yarkovsky effect estimation for some asteroid pairs with close orbits

E. D. Kuznetsov[1], A. E. Rosaev[2] and E. Plavalova[3]
[1]Ural Federal University, Lenina Avenue, 51, Yekaterinburg, 620000, Russia, eduard.kuznetsov@urfu.ru,
[2]Yaroslavl State University, Sovetskaya Street,14, Yaroslavl, 150000 Russia, hegem@mail.ru,
[3]Mathematical Institute of the Slovak Academy of Sciences, Stefanikova 848/49, 81473, Bratislava, Slovakia plavalova@komplet.sk

Introduction

The mutual asteroid collisions and disruptions may be an important source of meteoritic flux on Earth. In this aspect, studying very young asteroid families and pairs, which are originated in such events has a great interest.

Theoretical Background

- It is known, that non-gravity thermal effects play an important role in small bodies dynamics. The fundament of Yarkovsky effect theory was established in papers (Vokrouhlicky 1998, Vokrouhlicky 1999). The Yarkovsky effect has still not been measured in the main belt, thus Spoto et al. (2015) used a calibration based on asteroid (101955) Bennu to compute the ages of more than 50 families in the main belt. In this paper we have calculated the values of maximal Yarkovsky acceleration for some pairs of asteroids with very close orbits and (potentially) very small ages.
- As it is well known, non-gravitational tangential acceleration may be expressed as (Marsden 1973):

$$a_\tau = A_2\left(\frac{r_0}{r}\right)^d\ t$$

- Here $r_0 = 1$, $d \approx 2.25$, r is heliocentric distance of asteroid, t is a time. Coefficient A_2 depends on physical parameters of asteroid. After the integration of equation above it is possible to obtain (Vokrouhlicky 1998):

$$\frac{da}{dt} = -\frac{8}{9}\frac{(1-A)\,\Phi}{n}W(K,R)\cos\phi\,.$$

- Here n is the mean motion; Φ is the standard radiation force factor, which is inversely proportional to the bulk density ρ, the diameter of asteroid D, and the square of the orbital distance r. The Bond albedo A expressed through geometric albedo p_v as $A = 1/3\,p_v$. Function $W(K,R)$ is determined by the thermal parameters of the body and a frequency. From (Vokrouhlicky 1998), we have:

$$W(K,R) \approx -\frac{1}{5}\,.$$

- Simple account of the Yarkovsky effect in semimajor axis may be obtained by normalization using (101955) Bennu parameters, because it is known with smallest error (Spoto et al. 2015):

$$\dot{a} = \frac{da}{dt} = \left(\frac{da}{dt}\right)_B \frac{\sqrt{a_B}(1-e_B^2)D_B}{\sqrt{a}(1-e^2)D}\frac{\rho_B\cos\phi}{\rho\cos\phi_B}\frac{1-A}{1-A_B}.$$

- The symbols with a "*B*" refer to asteroid (101955) Bennu. The value of $\dot{a}_B = (19 \pm 0.1)\cdot 10^{-4}$ au/Myr and not critically depends on d (Farnocchia et al. 2013). After the substitution of (101955) Bennu physical parameters (Del Vigna et al. 2018), we obtain for the Yarkovsky semimajor axis drift (in au/Myr):

$$\dot{a} = \frac{da}{dt} = 12.09\cdot 10^{-4}\frac{\cos\phi}{\sqrt{a}(1-e^2)D}\frac{1-A}{\rho}.$$

- For the obliquity we have $-1 \le \cos\phi \le 1$, for the density we can accept $1.0 \le \rho \le 3.3$ g/cm^3. However for more exact estimation, we can take into account spectral type of studied asteroids. Exact determinations of first of all density and obliquity from observations is difficult. On the other word, we can give restrictions on density and obliquity of asteroids in assumption of forming breakup at encounter close to epoch *T*.
- The coefficient $(1-A)$ usually is very close to the unit. By acception for density value $\rho = 1.1$ g/cm^3 and for obliquity $\cos\phi = \pm 1$ we obtain the maximal value of modulus of semimajor axis drift $|\dot{a}|$ for any studied asteroid. This value is slightly overestimated due to the underestimated value of density.
- In assumption of equal albedo *A*, radius *R* of asteroids in dependence of absolute magnitude *H* may be estimated by (Bowell et al. 1989):

$$R(km) = \frac{D}{2} = 1329\frac{10^{-H/5}}{2\sqrt{A}}\,.$$

- The values of absolute magnitudes and albedo was taken in Horizons web site (https://ssd.jpl.nasa.gov/horizons.cgi).
- As a result, we can estimate most probable value of $|\dot{a}|$. As an example, we give results of our calculations for some asteroid pairs with common origin from (Pravec et al. 2019) (see Table 1).

Table 1. Maximal modulus of the semimajor axis drift

#pair	Asteroid	*H* [mag]	*D* [km]	*a* [au]	$\lvert\dot{a}\rvert$ [10^{-4} au/Myr]
1	(1741)Giclas	11.4	10.62	2.88320	0.536
	(258640) 2002 ER36	15.8	1.40	2.88572	4.065
2	(2110) Moore-Sitterly	13.4	6.41	2.19854	1.130
	(44612) 1999 RP27	15.5	2.20	2.19804	3.249
3	(3749) Balam	13.3	4.54	2.23699	1.442
	(312497) 2009 BR60	17.7	0.60	2.23656	10.943
4	(4765) Wasserburg	13.8	2.15	1.94574	2.282
	(350716) 2001 XO105	17.6	0.37	1.94574	13.135
5	(4905) Hiromi	12.2	9.76	2.60132	0.667
	(7813) Anderserikson	13.1	6.04	2.60032	1.068
6	(5026) Martes	13.9	8.00	2.37782	1.842
	2005 WW113	17.8	1.33	2.37756	11.10
7	(6369) 1983 UC	14.2	3.34	2.29269	2.009
	(510132) 2010 UY57	18.2	0.53	2.29294	12.677
8	(7343) Ockeghem	14.3	2.92	2.19294	2.297
	(154634) 2003 XX38	16.8	0.92	2.19276	7.264
9	(8306) Shoko	14.9	2.42	2.24199	2.887
	2011 SR158	18.1	0.55	2.24136	12.602
10	(9783) Tensho-kan	14.06	4.40	2.66889	1.448
	(348018) 2003 SF334	17.1	1.08	2.66844	5.874
11	(10123) Fideoja	14.55	2.29	2.26930	2.834
	(117306) 2004 VF21	16.4	0.98	2.26905	6.644
12	(17198) Gorjup	15	2.31	2.27942	2.883
	(229056) 2004 FC126	17.5	0.73	2.28066	9.116
13	(21436) Chaouchi	15.3	2.29	2.18625	3.030
	(334916) 2003 YK39	18.2	0.60	2.18663	11.519
14	(25021) Nischakumar	15.7	2.19	2.31840	3.138
	(453818) 2011 SJ109	18.4	0.63	2.31733	10.882
15	(25884) Asai	14.7	1.45	1.95432	4.192
	(48527) 1993 LC1	16.1	1.39	1.95430	5.146
16	(26416) 1999 XM84	14.3	3.18	2.34188	2.044
	(214954) 2007 WO58	16.8	1.01	2.34234	6.464
17	(26420) 1999 XL103	15.7	1.67	2.19730	4.058
	2012 TS209	18.4	0.48	2.19707	14.070
19	(43008) 1999 UD31	15.7	1.67	2.34803	4.024
	(441549) 2008 TM68	17.5	0.73	2.34733	9.225
20	(44620) 1999 RS43	15.6	1.75	2.17589	3.956
	(295745) 2008 UH98	17.6	0.70	2.17656	9.932
21	(46829) McMahon	15.0	2.31	2.40021	2.872
	2014 VR4	18.0	0.58	2.40056	11.434
22	(49791) 1999 XF31	15.8	0.86	2.31640	4.226
	(436459) 2011 CL97	18.4	0.26	2.31658	13.98
23	(52852) 1998 RB75	14.8	2.15	2.26263	2.985
	(250322) 2003 SC7	16.8	0.86	2.26294	7.497
24	(80218) 1999 VO123	16.6	1.18	2.21814	5.631
	(213471) 2002 ES90	16.9	1.04	2.21872	6.466

Numerical Simulation

- To study the dynamical evolution of some selected close asteroid pairs, the equations of the motion of the systems were numerically integrated 50 kyrs into the past, using the N-body integrator Mercury (Chambers 1999).
- We made three series of integration. In the first we use only large planets perturbations. In the second we add Ceres, Vesta, Juno and Pallas. In the third series of our numeric integration we try estimate non-gravitational Yarkovsky effect. In addition to distance during encounter, we perform calculation relative velocity along integration by Nesvorný and Vokrouhlický (2006) and by our previous paper (Rosaev and Plavalova 2018) expression.
- In some cases we obtain for the pair age values very different from the values in (Pravec 2019) (see Table 2 and Fig. 1-3). This problem required of the future careful studying in each case.

Table 2. Estimations of ages of the asteroid pairs

#pair	Asteroid	Asteroid	Age, kyrs (Pravec 2019)	Age, kyrs (nominal Mercury)
1	(5026) Martes	2005 WW113	18	18
2	(1741) Giclas	(258640) 2002 ER36	200	180
3	**(3749) Balam**	**(312497) 2009 BR60**	**400**	**270**
4	**(46829) McMahon**	**2014 VR4**	**800**	**150**
5	(4765) Wasserburg	(350716) 2001 XO105	200	100

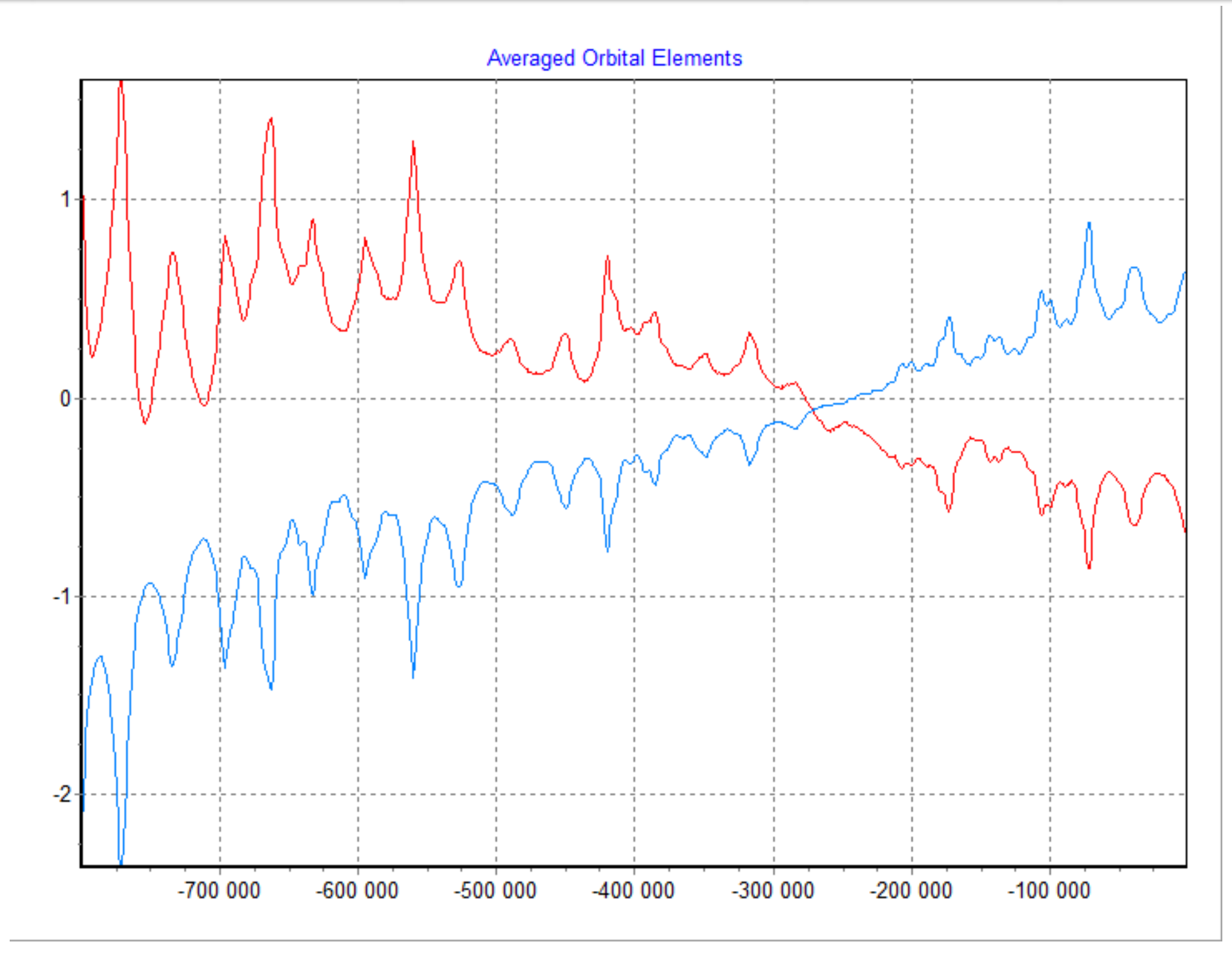

Figure 1. *Difference between the argument of perihelium and the longitude of ascending node vs time (years) for the pair **(3749) Balam - (312497) 2009 BR60***

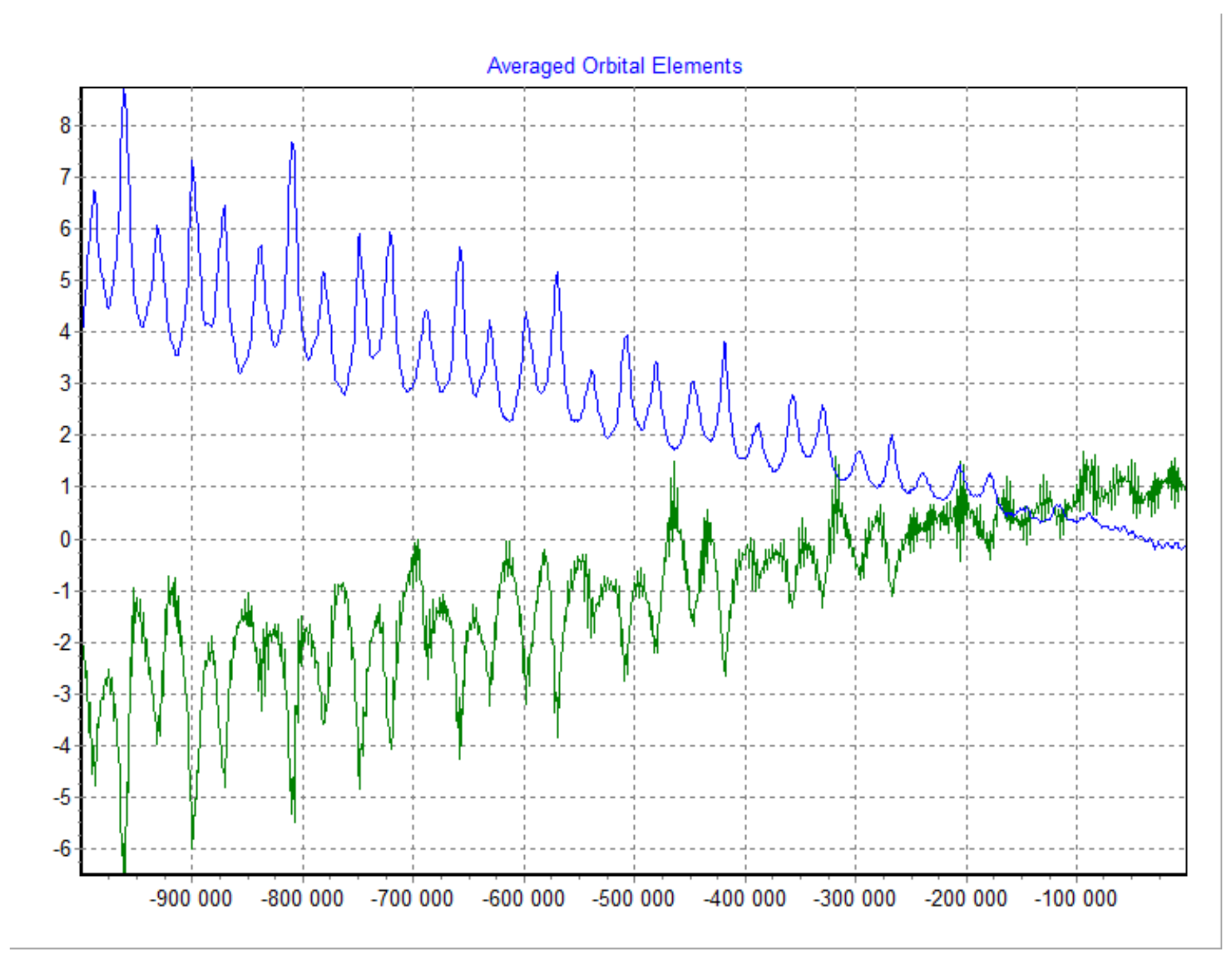

Figure 2. *Difference between the argument of perihelium and the longitude of ascending node vs time (years) for the pair **(46829) McMahon - 2014 VR4***

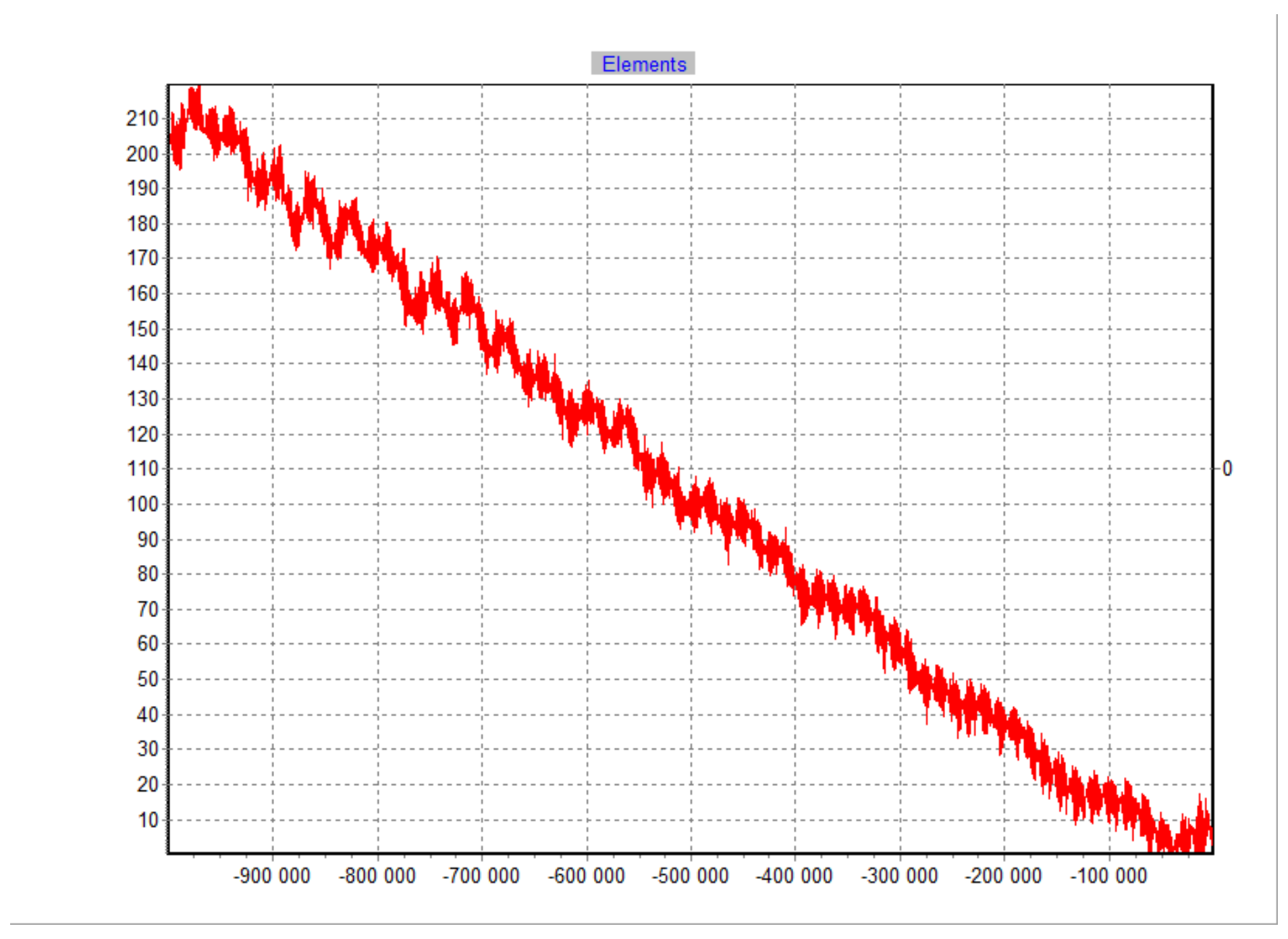

Figure 3. *z-component of relative velocity (m/s) for the pair **(46829) McMahon - 2014 VR4***

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