Photometric observations of the unrelaxed binary near-Earth asteroid (35107) 1991 VH in support of the NASA Janus space mission – Detection of a spin-orbit interaction

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Discovery observations

Near-Earth asteroid 1991 VH – discovered by Rob McNaught from Siding Spring on November 9, 1991.

Binary nature of the asteroid – discovered by Pravec et al. (1998) from photometric observations taken with the 0.65-m telescope from Ondřejov during 1997 February 27 to April 4. They measured the basic parameters of the binary system (P_{prim}, P_{orb}, D_{sec}/D_{prim}, a) and estimated a non-zero eccentricity of the mutual orbit $e = 0.07 \pm 0.02$.

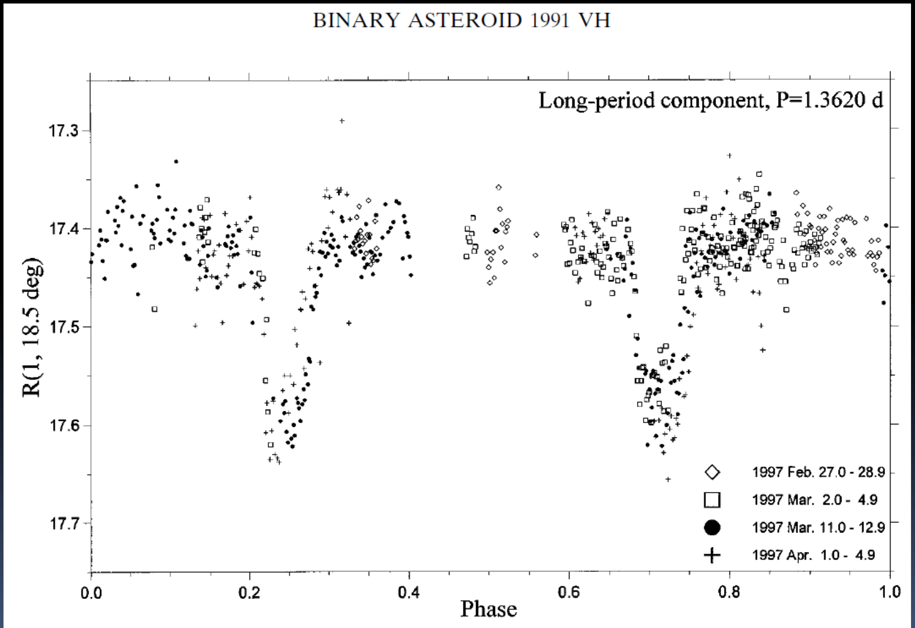


FIG. 5. Long-period lightcurve component. The epoch is JD 2450508.5.

Reference: Pravec et al., Icarus 133, 79-88 (1998)

Follow-up observations in 2003 and 2008

The asteroid had a favorable apparition in February 2003 → higher-quality follow-up observations taken with the Ondřejov 0.65-m.

Found a non-synchronous rotation of the secondary: P_{sec} = 12.836 ± 0.003 h (cf. P_{orb} = 32.67 h)

The secondary's equatorial elongation estimated a_s/b_s = 1.33 ± 0.10

Eccentricity refined to e = 0.05 ± 0.02 (3-σ error). Naidu et al. (2012) reported e = 0.05 from radar observations taken in 2008 as well, and they confirmed the non-synchronous secondary rotation.

Additional, shorter follow-up observations taken with the 0.65-m telescope in June/July 2008. The limited amount of data: a unique solution for P_{sec} not obtained, but the 2008 data didn't fit with the value 12.836 h observed in 2003 at all → Hint on that the secondary spin period is not constant.

(35107) 1991 VH is a unique unrelaxed asteroid binary system.

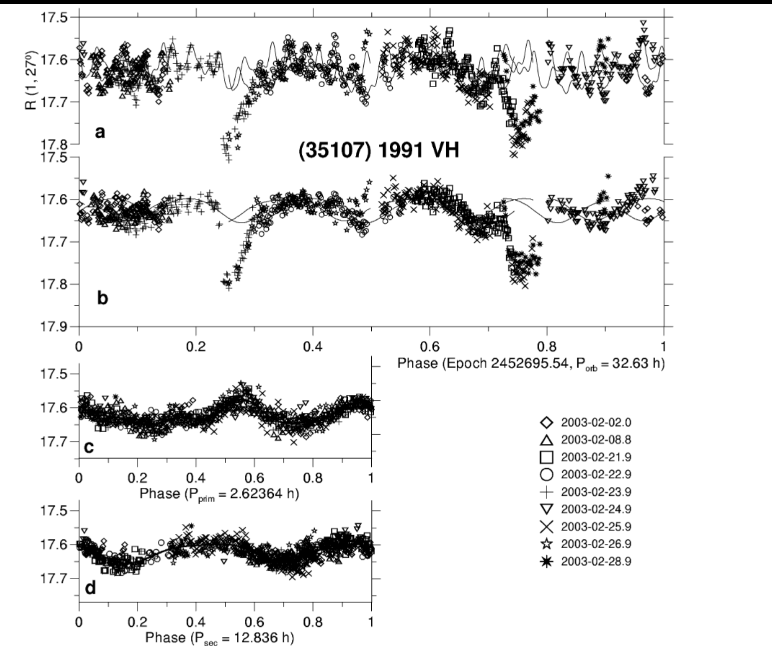


Fig. 12. Lightcurves of (35107) 1991 VH. (a) The original data showing the two rotational lightcurve components as well as the mutual events. The additive Fourier series with the periods of 2.6236 and 12.836 h was fitted to the rotation data. (b) The data showing the mutual events and the 12.836-h period variation after subtraction of the primary lightcurve component. (c) The primary lightcurve component. (d) The 12.836-h period lightcurve component (see text). $G = 0.26$.

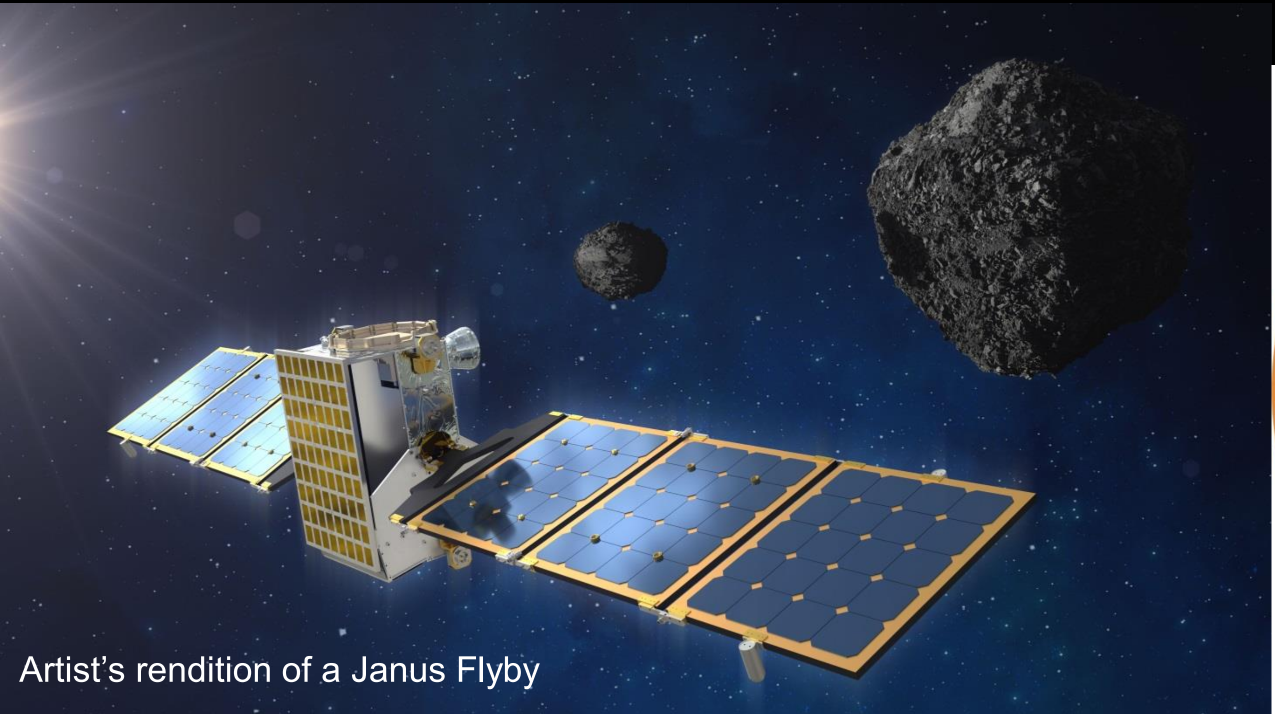
References: Pravec et al., Icarus 181, 63–93 (2006). Pravec et al., Icarus 267, 267–295 (2016). Naidu et al., AAS/DDA Meeting 43, 7.07 (2012)

Target for the Janus mission

The unreleaxed binary asteroid (35107) 1991 VH has been selected as a target for the NASA Janus mission. (The other target for the mission is the ordinary, relaxed binary asteroid (175706) 1996 FG3.)

The Janus spacecraft will launch with the Psyche mission in 2022. Following a 4 year cruise (including one Earth gravity assist), the spacecraft will fly by the binaries before March 2026. During the flybys the spacecraft will image the target binary asteroids in the visible and IR, coming within 100 km of the asteroids.

The Janus mission will provide unique and unprecedented information on binary asteroids, allowing insight into their rubble pile properties, their formation and their evolution.



Artist's rendition of a Janus Flyby

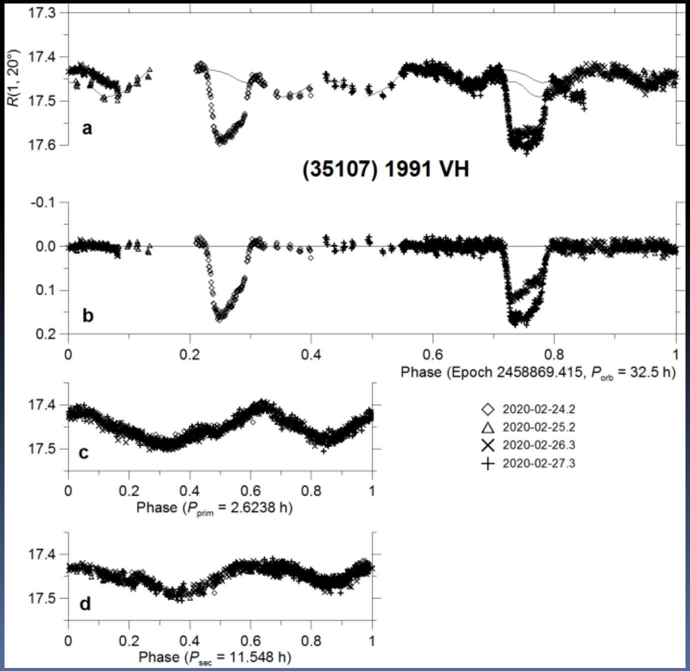
Photometric campaign of 2020

The asteroid had another favorable apparition in January-March 2020.

We took extensive high-quality photometric observations with the 1.54-m telescope on La Silla (29 nights), the 0.9-m Spacewatch telescope (9 nights) and the 2.2-m telescope on Mauna Kea (3 nights) from 2020-01-19 to -03-16.

Found that both the secondary spin period P_{sec} and the orbit period P_{orb} changed again since the previous apparitions.

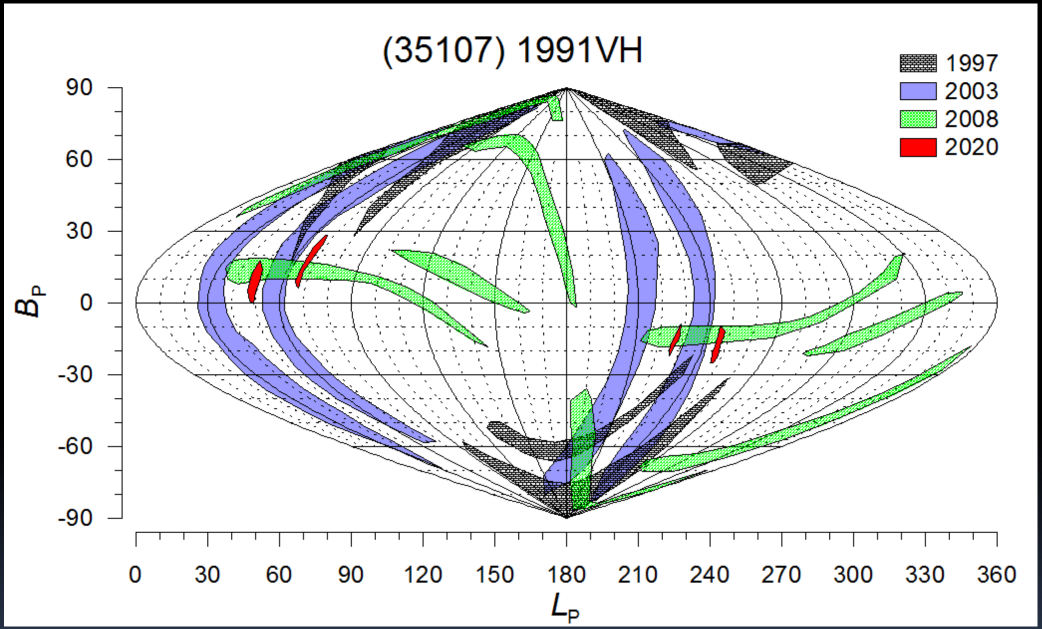
A small sample of the data:



Mutual orbit precessing

Modeling of the mutual orbit in the 4 observed apparitions: A model with constant orbit pole cannot explain the observations → inclined and precessing orbit.

Instantaneous orbit pole constraints in the individual apparitions:



Plausible speculation: The inclination of the orbit wrt the primary's equator may be moderate only (several degrees up to a few ten degrees) – the orbit pole may precess not far from the instantaneous orbit pole constrained by the best 2020 data.

Secondary spin and orbit periods

Table 1: Secondary rotation and orbit periods of 1991 VH

Epoch UT	P_{sec} (h)	$P_{\text{orb-syn}}$ (h)	$P_{\text{orb-prograde}}$ (h)	$P_{\text{orb-retrograde}}$ (h)
1997-03-17	n/a	32.69	32.68	32.72
2003-02-25	12.836	32.63	32.63	32.71
2008-07-01	(14.18)	32.80	32.84	32.76
2020-01-27	11.565	32.50	32.46	32.54
2020-02-18	11.777	dtto	dtto	dtto
2020-02-26	11.548	dtto	dtto	dtto
2020-03-02	11.612	dtto	dtto	dtto

3-σ uncertainties of P_{sec} are ≤ 0.02 h; the value in brackets is not unique.
3-σ uncertainties of the orbit periods are 0.01–0.07 h.
The orbit periods in 2020 were determined from all the data January-March.

Both the secondary rotation period P_{sec} and the orbit period P_{orb} show significant variations on an order of 1-2 h and 0.2 h, respectively, and they appear correlated.

Note: The observed (synodic) orbit periods $P_{orb\text{-}syn}$ were affected by the synodic effect, its magnitude was between 0.00 and 0.08 h (median 0.04 h) for the individual epochs and orbit poles. We corrected the values assuming the orbit pole is either prograde or retrograde and it is close to *(L, B) ~ (57, +15)* or *(237, -15).*

Secondary spin and orbital energy

The apparent correlation between the secondary rotation period P_{sec} and the orbit period P_{orb} leads us to look into a balance between the secondary rotation energy and the orbit orbital energy.

Our hypothesis is that the sum of the secondary rotation and the orbital energy is constant:

$$E_{\rm sec} + E_{\rm orb} = \frac{1}{2} I_2 \omega_2^2 - G\frac{M_1 M_2}{2a_{\rm orb}} = {\rm const.} \tag{1}$$

Using

$$I_2 = \frac{1}{5} M_2 (a_2^2 + b_2^2) \text{ and } n^2 a_{\rm orb}^3 = G(M_1 + M_2), \tag{2}$$

and approximating

$$M_1 \equiv V_1 \rho \doteq \frac{4}{3}\pi b_1^3 \rho, \tag{3}$$

we convert Eq. (1) to

$$\frac{1}{5}\left[\left(\frac{a_2}{b_2}\right)^2 + 1\right]\omega_2^2 - \frac{\left(\frac{4}{3}\pi G\rho n\right)^{\frac{2}{3}}}{X^2 \sqrt[3]{1+X^3}} = {\rm const.}, \tag{4}$$

where $X \equiv b_2/b_1$.

From Eq. (4), and as $n = 2\pi/P_{\rm orb}$ and $\omega_2 = 2\pi/P_{\rm sec}$, we can calculate a new $P_{\rm sec-fin}$ at a recent ('final') epoch with $P_{\rm orb-fin}$ from the original ('initial') values $P_{\rm sec-ini}$ and $P_{\rm orb-ini}$.

For 1991 VH, we have the secondary equatorial axis ratio $a_2/b_2 = 1.33$, the secondary-to-primary size ratio $X = 0.38$, and we assume $\rho = 2000\,{\rm kg/m^3}$. Then from the observed initial orbital and secondary spin periods
$P_{\rm orb-ini} = 32.67$ h and
$P_{\rm sec-ini} = 12.836$ h,
for the new observed orbital period
$P_{\rm orb-fin} = 32.50$ h
we get a new secondary spin period
$P_{\rm sec-fin} = 11.60$ h.

The predicted secondary period P_{sec} = 11.60 h for the 2020 epoch agrees with the observed values 11.548 to 11.777 h.

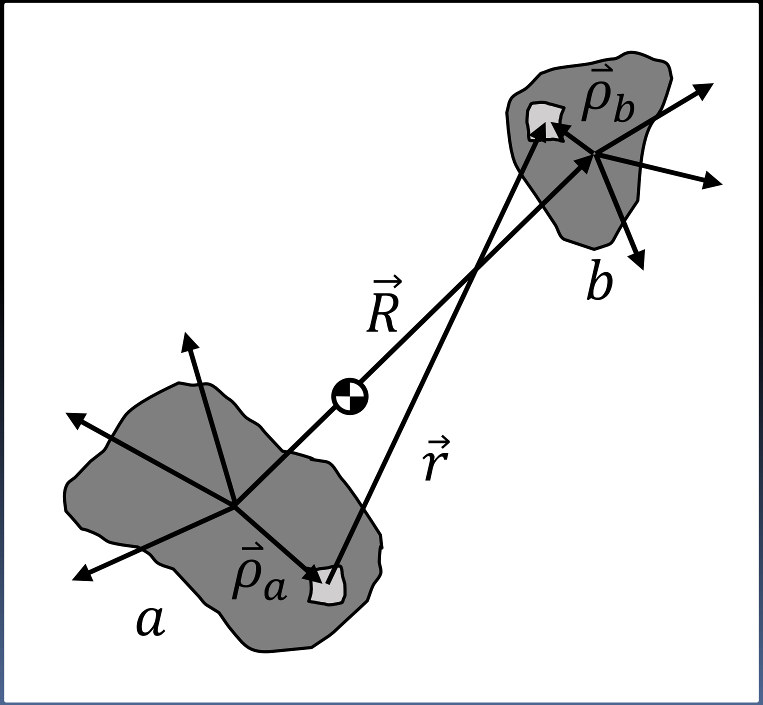
The observed changes of the secondary spin and orbit periods from 2003 to 2020 are consistent with an exchange of energy between the secondary rotation and orbital motion → spin-orbit interaction

Full Two Body Problem

Arbitrary masses in close proximity see significant spin-orbit coupling: Position and orientation of both asteroids are important.

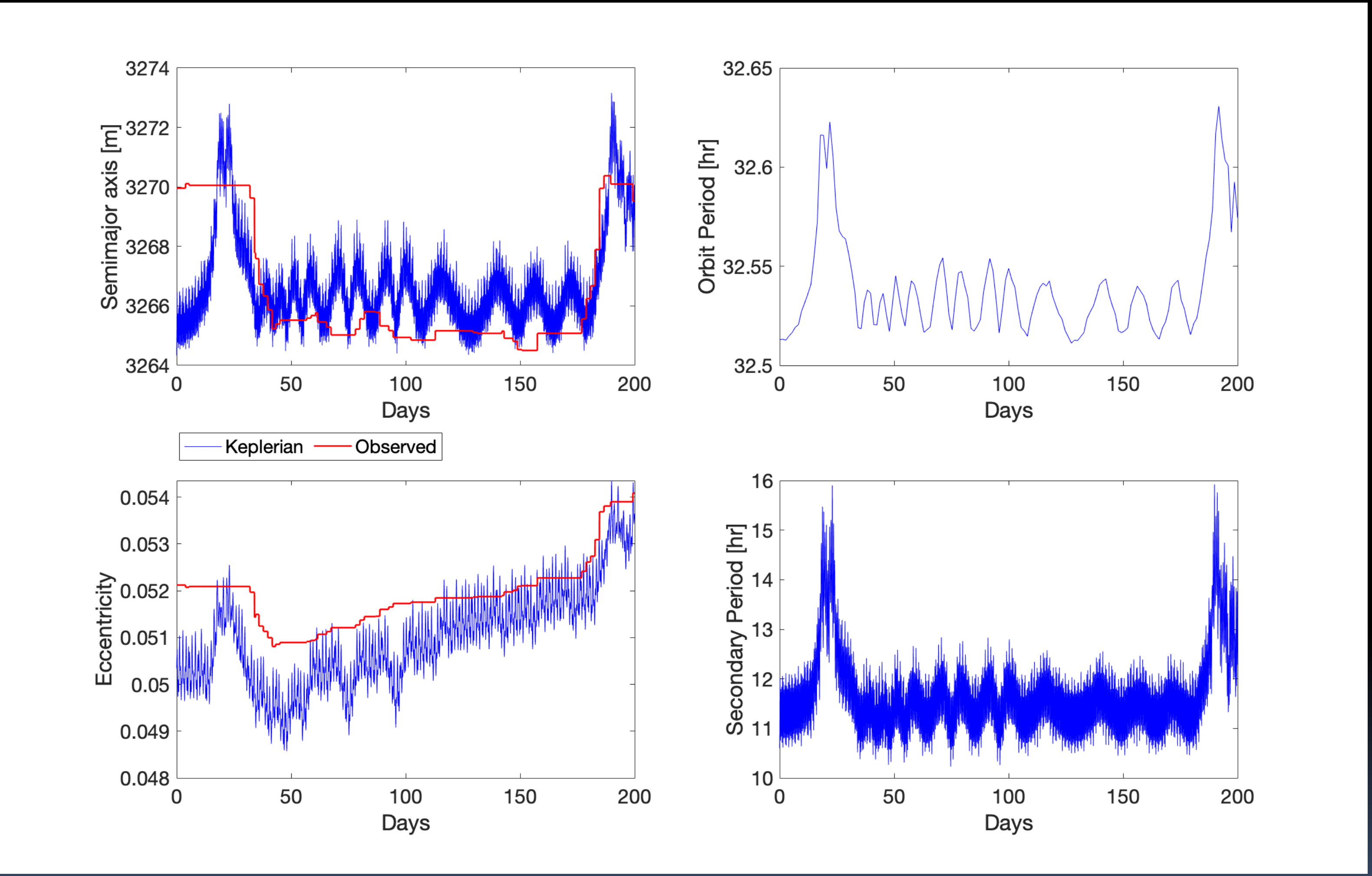
The mutual orbit does not follow Keplerian dynamics. The semimajor axis and eccentricity are found using the observed positions instead of Kepler's laws.

Numeric simulations are done using the General Use Binary Asteroid Simulator[1]



[1] https://github.com/alex-b-davis/gubas

1991 VH Numeric Simulations



The jumps in orbit period and secondary spin period are correlated with the secondary tumbling in its orbit. The observed elements are calculated using a 3-day window of the separation.

Conclusions

The binary near-Earth asteroid (35107) 1991 VH is in an unrelaxed state with inclined (precessing) and eccentric orbit and non-synchronous secondary (satellite) rotation.

The secondary spin period and the orbital period appear correlated. The observed changes of the periods from 2003 to 2020 suggest a spin-orbit interaction.

More thorough simulations of the full two body problem needed to get a better understanding of the unrelaxed binary system.