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Szilárd Csizmadia

`szilard.csizmadia@dlr.de`

Deutsches Zentrum für Luft- und Raumfahrt e. V. (DLR)

Viktória Fröhlich

HUN-REN CSFK Konkoly Observatory, MTA Centre of Excellence

Article

Keywords:

Posted Date: October 5th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10920393/v1>

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Additional Declarations: No competing interests reported.

Satellite-driven pathway to maintain the atmosphere of TNO 2002XV₉₃ - intense dynamical processes in the outer Solar System

Szilárd Csizmadia^{*1} and Viktória Fröhlich^{2,3}

¹Deutsches Zentrum für Luft- und Raumfahrt (DLR), Institut für
Weltraumforschung, Rutherfordstrasse 2, 12489 Berlin, Germany

²HUN-REN CSFK Konkoly Observatory, MTA Centre of Excellence,
Konkoly Thege M. út 15-17, Budapest, 1121, Hungary

³Eötvös Loránd University, Institute of Physics and Astronomy, Pázmány
Péter Sétány 1/A, Budapest, 1117, Hungary

Submission: 2026 September 3

Abstract

The recent discovery of the atmosphere around the ~ 255 -km-radius plutino (612533) 2002 XV₉₃ challenges the usual expectation that such a small trans-Neptunian object cannot retain a volatile atmosphere over long timescales. Regarding the observed atmosphere, two possible origins have been suggested: ongoing cryovolcanic activity or a recent impact. We point out that a so far undetected satellite can be the energy source of the cryovolcanism. We derive the relevant tidal heating scaling, the viable satellite parameter space, and outline direct observational tests of the proposed mechanism. For plausible icy-body parameters, 30–100 km diameter companions can sustain such an atmosphere for close, eccentric orbits. The hypothesis predicts a companion directly detectable through high-resolution imaging, rotational light-curve effects, and stellar occultation. Our model also predicts indirect detection possibilities by monitoring the atmospheric evolution via future additional stellar occultation measurements, which also helps to distinguish between impactor and satellite scenarios. Since we estimate the circularization timescale of the hypothetical moon to fall between 10^4 - 10^6 years, we point out that the outer regions of the Solar System still exhibit dynamically intense processes today.

1 Introduction

Arimatsu et al. [1] very recently reported that their stellar occultation measurements revealed an atmosphere of the Trans-Neptunian Object (TNO) 2002 XV₉₃. This new discovery poses a pressing question regarding studies of the properties of asteroids. The

^{*}corresponding author, e-mail: szilard.csizmadia@dlr.de

reported detection of such an atmosphere is unexpected because the object is substantially smaller than the classical volatile-bearing bodies Pluto, Triton, Eris, and Makemake [2].

Arimatsu et al. [1] inferred a surface pressure of 100–200 nbar from stellar-occultation data and discussed the difficulty of maintaining such an atmosphere on a body with radius $R_a \approx 255$ km. Note that the Jeans-parameter (the Jeans-parameter being $\lambda = v_{\text{esc}}^2/v_{\text{therm}}^2$ where v_{esc} is the gravitational escape velocity from a celestial body and v_{therm} is the mean thermal velocity in its atmosphere) is in the order of 1–3 for N_2 , Ar , CO or CH_4 atmospheres on this minor planet. This means that, in a naive Jeans model, the atmosphere escapes the asteroid within a few hours. Since the Jeans escape model may not be valid at such low surface temperatures (45 K, see [1]) and low pressures, Arimatsu et al. [1] concluded that the time scale of the atmospheric loss is in the order of 100–1000 years. This is still too low for a primordial atmosphere, so there must be a mechanism that recently birthed or continuously sustains the atmosphere. Two broad explanations were originally proposed: volatile release by cryovolcanic activity or transient production by the impact of a small icy body [1, 3]. But what drives this volcanic activity energetically was left open in [1].

Although the above-mentioned possibilities are not mutually exclusive, cryovolcanic activity [4] requires not only accessible volatiles but also an energy source capable of mobilizing or releasing such material. For a small, cold TNO, radiogenic heating alone is unlikely to explain. We therefore consider whether an external dynamical energy source could supply part or all of the required power.

We investigate whether the atmosphere of 2002 XV₉₃ could be sustained by cryovolcanic activity powered by satellite-driven tidal heating. The mechanism is analogous to the tidal heating of Io [5], although not necessarily in scale or geological expression. Such a scenario is plausible in the sense that satellites are common among small Solar System bodies, including trans-Neptunian objects (<https://www.johnstonsarchive.net/astro/astmoontable.html>).

A key prediction of the satellite-driven tidal-heating scenario is the presence of a companion capable of supplying the required internal heat. Such a companion could be searched for through high-resolution imaging, stellar occultations, rotational photometry, or long-baseline astrometry. Conversely, stringent non-detections of companions in the relevant separation and contrast regime would disfavour this mechanism and lend support to an impact origin, thereby constraining the collisional and dynamical state of the present-day outer Solar System.

2 Model

2.1 Atmospheric mass and required replenishment power

We assume the atmosphere is in hydrostatic equilibrium. For an asteroid of radius R_a , surface gravity g_a , and atmospheric pressure on the surface P_a , the total atmospheric mass is approximately

$$M_{\text{atm}} \simeq \frac{4\pi R_a^2 P_a}{g_a}. \quad (1)$$

We denote the mean bulk density of the asteroid by ρ_a and its mass by M_a , and we express the surface gravity as

$$g_a = \frac{GM_a}{R_a^2} = \frac{4\pi}{3} G \rho_a R_a, \quad (2)$$

74 where G is the Newtonian gravitational constant. Thus

$$M_{\text{atm}} \simeq \frac{3R_a P_a}{G\rho_a} \quad (3)$$

75 For $R_a = 255$ km, $P_a = 100 - 200$ nbar [1] and, assuming an icy composition for the main
76 body, $\rho_a = 0.5 - 1.5$ g cm $^{-3}$, this yields an atmospheric mass of

$$M_{\text{atm}} \sim (0.08 - 0.45) \cdot 10^{12} \text{kg} \quad (4)$$

77 The heating power needed to sustain such an atmosphere is set by the species being
78 volatilized, the available volatile reservoir, the escape and recondensation timescales, and
79 the efficiency with which internal heating is converted into atmospheric gas. Therefore, we
80 define a replenishment luminosity of

$$L_{\text{rep}} \simeq \frac{1}{\eta} \frac{M_{\text{atm}} \mathcal{L}_{\text{sub}}}{\tau_{\text{repl}}}, \quad (5)$$

81 which (albeit phenomenological) helps us to characterize the required tidal heating power.
82 Here $\mathcal{L}_{\text{sub}}$ is the effective volatile-release energy per unit mass (latent heat), τ_{repl} means
83 the atmospheric replenishment or loss timescale, and η is an efficiency factor in the order
84 of unity. Eq. (5) is not intended to define a unique physical model. Rather, it can be
85 used to set a threshold minimum value necessary for efficient tidal heating. All unknown
86 geological and microphysical processes are stored in the η -parameter.

87 The numerical value of the latent heat is estimated to be $\mathcal{L}_{\text{sub}} = (2 - 6) \cdot 10^5$ J/kg based
88 on [6, 7]. These values are used only for an order-of-magnitude energy budget estimation.
89 The actual value depends on the vapor-pressure law, surface temperature, and ice mixing
90 state.

91 The mass loss rate is given by

$$\dot{M}_{\text{atm}} = \frac{M_{\text{atm}}}{\tau_{\text{repl}}} \quad (6)$$

92 Therefore, if we take 100 and 1000 years for the replenishment time, we get from Eq. (4)
93 that

$$\dot{M}_{\text{atm}} \simeq (2 - 143) \text{ kg s}^{-1} \quad (7)$$

94 Substituting these numerical values, we have

$$L_{\text{rep}} \simeq \frac{1}{\eta} \cdot (0.4 - 86) \text{ MW}. \quad (8)$$

95 2.2 Power demand for cryovolcanism

96 Here we investigate how big heating power is a plausible threshold for atmosphere-supplying
97 cryovolcanism on 2002 XV $_{93}$. The total cryovolcanic heat budget may be larger than L_{rep} ,
98 as heat must also be transported through the crust. A simple conductive estimate is

$$\dot{E}_{\text{cond}} \simeq 4\pi R_a^2 f k_{\text{eff}} \frac{T_m - T_a}{d}, \quad (9)$$

99 where f is the fraction of the surface involved in the activity, k_{eff} is the effective thermal
100 conductivity of the crust, T_m is the melting temperature, T_a is the main body surface

Table 1: Adopted and explored parameters for the order-of-magnitude tidal-heating calculation.

Quantity	Symbol	Explored range	Comment
Primary radius	R_a	255 km	From Arimatsu et al. [1].
Primary density	ρ_a	0.5-1.5 g cm ⁻³	Plausible icy-body range.
Satellite density	ρ_s	0.5-1.5 g cm ⁻³	Set equal to ρ_a .
Surface pressure	P_a	100-200 nbar	Reported atmospheric pressure scale by [1].
Satellite diameter	D_s	10-100 km	Grid on: 10, 25, 32, 50, 63, 100 km
Scaled semimajor axis	a/R_a	≤ 15	–
Eccentricity	e	0–1	–
Tidal response	k_2/Q	10^{-4}	Poorly known for cold, small icy bodies.
Required power	L_{rep}	variable	MW to tens-of-MW scale in the fiducial estimate.

temperature, and d is the depth of the volatile reservoir. A global liquid layer, $f = 1$, would require very large luminosity: for water ice with $T_m \simeq 273$ K, $T_a \simeq 45$ K, $k_{\text{eff}} \simeq 2.5$ W m⁻¹ K⁻¹, and $d = 10$ –50 km [8, 9, 10, 11, 12, 13], Eq. (9) gives $\dot{E}_{\text{cond}} \sim 10$ - 50 GW. In contrast, ammonia-rich or otherwise antifreeze crusts may remain mobile at substantially lower temperatures, $T_m \simeq 176$ K, and a porous regolith can reduce the effective conductivity to $k_{\text{eff}} \sim 0.1$ - 0.5 W m⁻¹ K⁻¹ [8, 9, 10, 11, 12, 13]. In this case, localized activity over only $f \sim 10^{-3}$ of the surface gives conductive losses of order 0.4 - 5 MW, comparable to the atmospheric replenishment requirement.

The small surface gravity of 2002 XV₉₃ makes the mechanical requirement for volatile escape relatively modest. A reservoir at depth d must overcome a pressure of order

$$\Delta P > \rho_l \cdot g_a \cdot d + \sigma_t + P_a \quad (10)$$

where ρ_l is the density of the liquid and σ_t is the tensile strength of the fractured crust. The atmospheric pressure term is negligible, since $P_a \simeq 0.01$ - 0.02 Pa. For $\rho_l \simeq 1000$ kg m⁻³ and $g_a \simeq 0.11$ m s⁻², the lithostatic term is only

$$\rho_l g d \simeq 0.11 \text{ MPa} \left(\frac{d}{1 \text{ km}} \right). \quad (11)$$

What amount of power is needed to move the matter over the crust of the asteroid? To estimate this quantity, we recall that the mechanical work of the gas is $dW = \Delta P dV$ and the volume element is $dV = \rho_l dM$. Since we want to equalize the outgassing from the asteroid to be equal to the mass loss, we get that the power needed to drive the crust-crossing is

$$P_{\text{crust-crossing}} = 0.11 \text{ MPa} \times \left(\frac{d}{1 \text{ km}} \right) \frac{\dot{M}_{\text{atm}}}{\rho_l} \quad (12)$$

This parametrization yields $P_{\text{crust-crossing}} \simeq 0.01$ -0.03 MW for $d = 1$ km and 1-3 MW for $d=100$ km, depending on the density of the crust and the atmosphere loss. Summing up the upper limits of the requirements for the volatilization for the replenishment and the crust-crossing, we have 8 MW for the cut-off value. taking into account other unknown or less precise values, we set a more conservative 10 MW power demand limit (cf. e.g. [4, 14, 13]). This is also in agreement with the ranges in the previous section if we assume that the atmosphere is closer to the smaller mass loss rate regime.

2.3 Tidal heating by an unseen satellite

We consider a satellite of mass m_s whose orbit has a semimajor axis of a and an eccentricity of e . In the constant-phase-lag approximation, the eccentricity tide raised by the satellite on the primary dissipates power of

$$\dot{E}_{\text{tide}} \simeq \frac{21}{2} \frac{k_2}{Q} \frac{G m_s^2 R^5 n e^2}{a^6}, \quad (13)$$

where $n = 2\pi/P$ is the satellite mean motion (P is its orbital period), k_2 is the second-order Love number of the asteroid and Q is its tidal quality factor [5, 15]. The mean motion is obtained from Kepler's 3rd law as

$$n = \left[\frac{G(M_a + m_s)}{a^3} \right]^{1/2}. \quad (14)$$

The mass of the satellite is obtained from its diameter D_s and its mean bulk density ρ_s as

$$m_s = \frac{\pi}{6} \rho_s D_s^3 \quad (15)$$

Substituting equations (14) and (15) into equation (13) we got

$$\dot{E}_{\text{tide}} \propto \frac{k_2}{Q} \rho_s^2 \rho_a^{1/2} D_s^6 R_a^{-1} e^2 \left(\frac{a}{R_a} \right)^{-15/2}. \quad (16)$$

One can see that the tidal heating mechanism is highly sensitive to the size of the satellite and to the asteroid-satellite separation.

2.4 Roche limit and periapse safety

The tidal disruption phenomenon limits the range of close orbits as follows. The classical Roche limit is given by

$$a_{\text{Roche}} = C_{\text{Roche}} R \left(\frac{\rho_a}{\rho_s} \right)^{1/3}, \quad (17)$$

where $C_{\text{Roche}} = 2.44$ is valid for the case of a fluid satellite, and $C_{\text{Roche}} = 1.26$ for a rigid body [15]. We note that a less deformable body could survive closer to the primary.

When looking for plausible satellite orbits, we consider a cut-off limit. The nominal Roche limit for the perigee sets

$$a(1 - e) > a_{\text{Roche}}. \quad (18)$$

3 Results and discussion

We compute $\dot{E}_{\text{tid}}$ on a grid in satellite diameter, semimajor axis, and eccentricity. The explored diameters are $D_s = 10, 25, 32, 50, 63$, and 100 km. We note that the upper limit of 100 km is not a physical barrier, but an observational one, as larger equal-albedo companions would contribute a non-negligible fraction of the unresolved system flux and would be increasingly difficult to hide from photometric, astrometric, or high-angular-resolution constraints. The scaled semimajor axis runs up to $15 R_a$. Eccentricity limits are

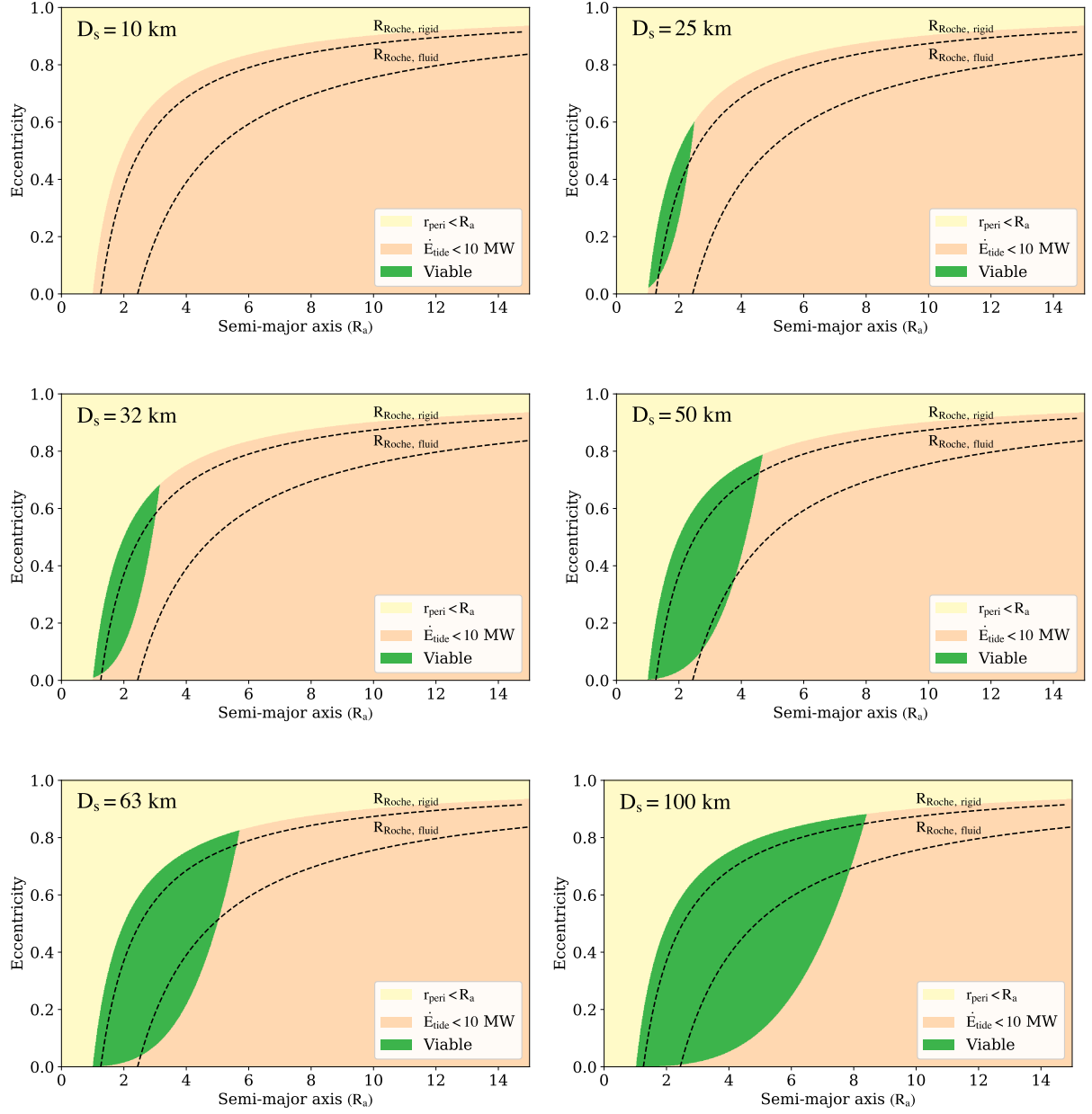


Figure 1: Scaled semi-major axis a/R_a vs eccentricity e for illustrating the tidal heating efficiency in asteroid 2002 XV93 assuming different moon sizes. Panels stand for $D_s = 10 \text{ km}$ (panel a), 25 km (panel b), 32 km (panel c), 50 km (panel d), 63 km (panel e), and 100 km (panel f), respectively. Yellow regions correspond to an orbital parameter space where the pericenter of the orbit falls below the radius of the TNO. Regions where tidal heating does not reach a luminosity of 10 MW are shown in orange. Moons located in the green regions have a physically possible orbital configuration and can drive tidal heating capable of supporting an atmosphere on the main body. The Roche limit is denoted by black dashed lines in both the fluid and the rigid approximation. Models assume $k_2/Q = 10^{-4}$ and $\rho_a = \rho_s = 1 \text{ g cm}^{-3}$.

Table 2: Qualitative outcome of the tidal-heating grid.

Satellite diameter	Periapse-safe cut, $a(1 - e) > a_R$
10 km	No viable solutions in the fiducial model.
25 km	Generally insufficient.
32 km	Mostly eliminated unless assumptions are optimistic.
50 km	May remain viable in part of the parameter space.
63 km	First robust periapse-safe solutions in the fiducial estimate.
100 km	Viable over a substantial part of the close-orbit parameter space.

0 and 1. At each grid point, we compare the dissipated power with the adopted threshold L_{rep} ,

$$\dot{E}_{\text{tide}} \geq L_{\text{rep}} = 10\text{MW}. \quad (19)$$

Grid points satisfying Eq. (19) are classified as viable. The results are shown in Figure 1.

In the fiducial calculation, all satellites below 25 km diameter are too small to provide the required power at any eccentricity value, or they must orbit the asteroid within the Roche-limit (panels a and b of Figure 1). The first viable solutions appear at a satellite diameter of 32 km, but they are confined to close, moderately eccentric orbits near the rigid Roche limit (panel c). For a satellite to orbit outside the fluid Roche limit, its diameter must be $\gtrsim 50$ km and its eccentricity must be $\simeq 0.2 \pm 0.1$ (panel d). More robust and plausible solutions occur for 60–100 km-class satellites (panels e and f). Even in these most robust cases, the satellite must not orbit farther than $\simeq 8R_a$ and its eccentricity needs to sit below $\simeq 0.65$. As such, we establish a minimum satellite diameter of $\simeq 60$ km to sustain an atmosphere of 100 nb on asteroid 2002 XV₉₃ via tidally driven cryovolcanism. Note that this value still depends on the adopted tidal response and volatile efficiency (k_2/Q , η values).

Overall, calculations show that satellite-driven tidal heating can drive cryovolcanism on 2002 XV₉₃ even at relatively small eccentricities ($e = 0.1 \dots 0.2$) in the case of 32–100 km diameter satellites. A distant, circular, or very small satellite would be dynamically interesting but energetically irrelevant.

4 Detectability of the satellite companion

A satellite capable of producing measurable tidal heating is likely to reside on a close-in orbit and may be intrinsically faint. At the heliocentric distance of 2002 XV₉₃, even a 50–100 km companion could therefore be difficult to detect directly. Nevertheless, several complementary observational approaches may provide useful constraints.

Figure 1 suggests that larger moons that produce tidal heating on this asteroid are closer to the minor planet than $\simeq 8R_a$ (this in accordance with the results of [28]). Using the rewritten form of Kepler’s third law [20]:

$$P_s^2 = \frac{3\pi}{G\rho_a \left(1 + \frac{\rho_s}{\rho_a} \left(\frac{R_s}{R_a}\right)^3\right)} \left(\frac{a}{R_a}\right)^3. \quad (20)$$

Assuming the same 0.5 g cm^{-3} density for both asteroid and satellite, $a/R_a = 10$, and 50 and 255 km radii for the satellite and the asteroid, respectively, we obtain that the

satellite’s orbital period around the asteroid is $P_s \approx 6$ days. Note that for $a/R_a = 3$ the period is 1 day.

Direct imaging is challenging, but not necessarily out of reach (cf. [16]). For $a/R_a = 20$, the projected angular separation is only ~ 0.15 arcsec, while the expected satellite–primary contrast is at most ~ 3.5 mag in the optical for the largest assumed satellite size. Such separations and contrasts are most plausibly accessible with high-angular-resolution facilities, including JWST, HST, or large ground-based telescopes equipped with adaptive optics, such as Keck or the VLT.

Long-baseline astrometry provides another possible way to search for the satellite [19].

A satellite may also produce mutual occultation events with the primary, which could in principle be detected photometrically [16, 22]. We estimate that the geometric transit probability is relatively high, ranging from 5–60% depending on the scaled semi-major axis (see Tab. 3). The expected transit depths, corresponding to events in which the satellite occults the primary, are listed in (Tab. 4). Emphasise that the feasibility of this method is limited by the faintness of 2002 XV₉₃. For comparison, TESS has detected a 0.21% transit around a $V = 10$ mag star [21], whereas 2002 XV₉₃ is typically only $V \simeq 20.5$ mag. Detecting comparable events for 2002 XV₉₃ would therefore require substantially greater collecting area and photometric precision than are available from current wide-field space photometry missions.

The reflected-light modulation of the satellite may be as small as ~ 1 mmag if its surface is homogeneous. In the extreme case of a strong hemispheric albedo asymmetry, however, the amplitude could reach $\sim 4\%$. Such a signal would still be challenging to detect for a $V \simeq 20$ mag object. Still, the relatively long orbital period of the satellite, of order 1–10 days, would allow long integrations and phase-binned photometry.

Stellar occultations may nevertheless remain the most promising approach (see, e.g., [17, 18]). Future occultation campaigns could search not only for the main atmospheric light-curve signature, but also for short secondary events occurring before or after the primary occultation. Because the satellite orbital period is relatively long, a favourable projected configuration would be required for any individual ground-based occultation. Repeated occultation campaigns would therefore be important, as they increase the probability of sampling the satellite close to conjunction with the primary on the sky.

Multi-chord occultations are especially valuable because they constrain the projected event geometry and can help distinguish atmospheric refraction from timing anomalies caused by a companion. Repeated occultations are therefore crucial for discriminating between the proposed scenarios.

Regarding the lifetime of the atmosphere, the impact and satellite-driven scenarios make distinct predictions for future observations. In the impact scenario, the atmosphere is expected to be transient: after a recent collision, the pressure should decline as volatile material escapes, recondenses, or is photochemically processed. Satellite-driven heating, by contrast, could sustain recurrent or quasi-persistent atmospheric replenishment, provided that the orbital eccentricity of the system is maintained. The two models therefore predict different temporal evolution of the atmosphere.

The two scenarios also differ dynamically. An impact origin does not require a surviving companion, whereas satellite-driven heating does. In the latter case, the atmosphere would act as an indirect tracer of a previously unresolved binary or satellite system, providing a direct observational test of the mechanism.

Table 3: First-order geometric probabilities for mutual eclipses in a circular satellite orbit around 2002 XV93. The values were computed as $P_{\text{ecl}} \simeq (R_a + R_s)/a$, assuming $R_a = 255$ km.

D_s	Geometric eclipse probability				
	$a = 2R_a$	$a = 3R_a$	$a = 5R_a$	$a = 10R_a$	$a = 20R_a$
10 km	51.0%	34.0%	20.4%	10.2%	5.1%
25 km	52.5%	35.0%	21.0%	10.5%	5.2%
50 km	54.9%	36.6%	22.0%	11.0%	5.5%
100 km	59.8%	39.9%	23.9%	12.0%	6.0%

Table 4: Expected depths of secondary mutual events, when the satellite is hidden behind 2002 XV93 or enters its shadow. The calculation assumes equal geometric albedos for the primary and the satellite, so that $F_{\text{moon}}/F_{\text{TNO}} \simeq (D_{\text{moon}}/D_{\text{TNO}})^2$, with $D_{\text{TNO}} = 510$ km.

D_s	$F_{\text{moon}}/F_{\text{TNO}}$	Relative depth δ_{sec}	Depth
10 km	3.84×10^{-4}	0.038%	0.42 mmag
25 km	2.40×10^{-3}	0.240%	2.61 mmag
50 km	9.61×10^{-3}	0.952%	10.4 mmag
100 km	3.84×10^{-2}	3.70%	41.0 mmag

5 Caveats

Our model exhibits several caveats. First, as noted before, k_2/Q is poorly known for a cold, small, porous, possibly differentiated trans-Neptunian body. The tidal response may differ by orders of magnitude from our assumed value.

Second, tidal forces lead to tidal decay and circularization of the orbit (decreasing a and loss of eccentricity). In an isolated, doubly synchronous primary–satellite system, the characteristic damping time is [15]:

$$\tau_e = \frac{1}{e} \frac{de}{dt} \simeq \left[\frac{21}{2} n \left(\frac{k_{2,p}}{Q_p} \frac{m_s}{M} \left(\frac{R}{a} \right)^5 + \frac{k_{2,s}}{Q_s} \frac{M}{m_s} \left(\frac{r_s}{a} \right)^5 \right) \right]^{-1}. \quad (21)$$

For the close, energetically relevant satellite orbits considered here, this gives a typical eccentricity-damping time scale of order $10^4 - 10^6$ yr, depending mainly on the poorly known tidal factors $k_{2,p}, k_{2,s}, Q$. The semimajor-axis evolution is given by [15] as:

$$\tau_a = \frac{a}{|\dot{a}|} = \frac{1 - e^2}{2e^2} \tau_e, \quad (22)$$

which gives orbital-decay timescales roughly one to two orders of magnitude longer than τ_e . Thus, in the absence of additional perturbations, resonances, or a recent excitation event, tidal heating at the ~ 10 MW level would be transient rather than sustainable over Gyr timescales. We emphasise that in this case, if the moon was captured by the main body, the capture event must have happened within the τ_e timescale.

The eccentricity of a tidally heated satellite could be maintained by additional companions, as in resonant satellite systems (e.g. [15]). In the absence of eccentricity excitation, tidal dissipation would tend to circularize the orbit and reduce the heating rate. Several possibilities, therefore, remain open. First, 2002 XV₉₃ may host more than one satellite.

Second, the satellite eccentricity may have been excited by a recent close encounter or impact event. Third, the satellite responsible for the tidal heating may have been captured only recently, within the last few Myr or even the last few 10^4 yr, depending on the tidal parameters and rheology of the primary. At present, we cannot distinguish between these scenarios. In all cases, however, the satellite-driven interpretation would point to recent or ongoing dynamical activity in the outer Solar System.

The sense of a satellite’s orbit relative to the primary’s spin fundamentally controls its tidal fate: a prograde moon migrates outward once its orbit circularizes and it lies beyond the (eccentricity-dependent) corotation distance, whereas a retrograde moon decelerates both the primary’s spin and its own motion and decays inward irrespective of eccentricity [27]. For a hypothesized companion of 2002 XV₉₃, this distinction bears directly on survival: retrograde satellites within a few tens of primary radii are expected to spiral in and be lost over the age of the Solar System for plausible dissipation factors [28, 29], so a surviving close-in moon capable of driving tidal heating would most plausibly be prograde.

We also call the attention to the scenario that a retrograde - and hence likely captured - satellite has fast enough tidal decay time that it can be the impactor itself. A prograde satellite if it rotates (rotated) slowly can be the impactor as well. In such cases the tidal decay time is still in the order of a million year so if a moon was the impactor, then its impact caused or extended the already existing atmosphere.

As a third caveat, 2002 XV₉₃ must have an internal structure that allows tidal heat to access volatile-rich material - a structure that we are as of yet unable to map precisely. Since tidal dissipation is generally expected to occur outside the core, cryovolcanism requires that the heating be generated within, or efficiently transported to, a volatile-bearing layer.

As a final note regarding caveats, the Roche limit used here is approximate. Real, small satellites usually have irregular shapes, high porosity, and spin states that alter the disruption boundary.

These uncertainties do not affect our main conclusion: satellite-driven tidal heating occupies a restricted, but still reasonably broad and observationally accessible region of parameter space. It therefore provides both a plausible explanation for the atmosphere of 2002 XV₉₃ and a testable hypothesis. The same observational tests can also help distinguish between the impact and satellite-driven scenarios for the origin of the atmosphere of the TNO 2002 XV₉₃.

6 Conclusions

The atmosphere detected around 2002 XV₉₃ requires a recent or ongoing source of volatile replenishment. While cryovolcanism and a recent impact have both been proposed as possible origins [1], we argue that cryovolcanism could be sustained by a satellite on a close, eccentric orbit. In this scenario, tidal dissipation provides an external dynamical heat source, linking the atmosphere directly to the architecture of an unresolved satellite system. The resulting atmosphere could persist for kyr–Myr timescales, unlike the short-lived atmosphere expected from an isolated impact or episodic outgassing event. The satellite-driven interpretation is therefore not only a plausible source mechanism, but also a testable hypothesis: monitoring the atmosphere and searching for a companion provide complementary ways to distinguish between the proposed scenarios. Our conclusions are the following.

1. Because tidal heating scales steeply with satellite size, $\dot{E}_{\text{tide}} \propto D_s^6$, 10–25 km satellites

are unlikely to maintain the atmosphere of 2002 XV₉₃ unless they orbit very close to the Roche limit.

2. Viable solutions first emerge for satellite diameters of order 30 km near the Roche boundary. More conservative, periaapse-safe solutions require larger companions, typically 50–100 km in diameter.
3. A key prediction of this scenario is the presence of a close companion. This makes the model testable through high-resolution imaging, repeated stellar occultations, and time-resolved photometry. The geometric probability of the eclipse is $\gtrsim 10\%$, while the relative depth of an occultation is estimated to be around $\gtrsim 10$ mmag.
4. The required eccentricity is expected to damp rapidly, with circularization timescales of only $10^4 - 10^6$ yr depending on tidal parameters and the rheology of the primary. Sustaining the tidal heating scenario, therefore, points to recent or ongoing dynamical activity, such as perturbations from an additional satellite, excitation by a passing body or impactor, or, most probably, a recent capture of the satellite.

Searching for a 30–100 km-class satellite around 2002 XV₉₃ is therefore as important as monitoring the atmosphere itself. If such a companion is found, it would not only provide a plausible energy source for satellite-powered cryovolcanism, but would also identify 2002 XV₉₃ as a dynamically informative trans-Neptunian binary system [16, 23]. If the companion orbit is eccentric, the short circularization time inferred here would further point to recent eccentricity excitation or to an additional mechanism maintaining eccentricity in the present trans-Neptunian dynamical environment [23, 24, 25, 26].

Data availability

No new observational data are reported in this draft. The numerical data used to generate Fig. 1 are publicly available at <http://www.transits.hu/> via the download links at the bottom of the page.

Code availability

The code used to compute the tidal-heating parameter grid will be made available at www.transits.hu upon publication.

Acknowledgements

V. F. acknowledges financial support from the undergraduate research assistant program of the Konkoly Observatory.

The authors thank Dr Zsolt Regaly (Konkoly Observatory, Hungary) for the discussion about the retrograde moon orbit scenario.

Author contributions

Sz.Cs. conceived the satellite-driven tidal heating scenario and wrote the initial manuscript draft. V.F. contributed to the physical interpretation and manuscript development. Both authors discussed the results and approved the final manuscript.

Competing interests

The authors declare no competing interests.

Use of generative artificial intelligence

During manuscript preparation, the authors used ChatGPT for language editing and assistance in literature searches. All references, numerical values, scientific content, calculations, interpretations and conclusions were independently verified and approved by the authors.

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