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What long-term data can tell us about Molniya: past works and open points

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MOLNIYA CONSTELLATION

VERY RICH DYNAMICAL ENVIRONMENT:

a perfect laboratory for different dynamical systems tools and perspectives

- **Semi-synchronous orbit:** 12 hour orbital period — tesseral resonance
- **Highly elliptical orbit**: $a \approx 26550$ km, $e \approx 0.73$ — lunisolar perturbation and atmospheric drag
- **Critical inclination**: $i \approx 63.4$ degrees — $\dot{\omega}_{J_2} \approx 0$

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ACKNOWLEDGMENTS

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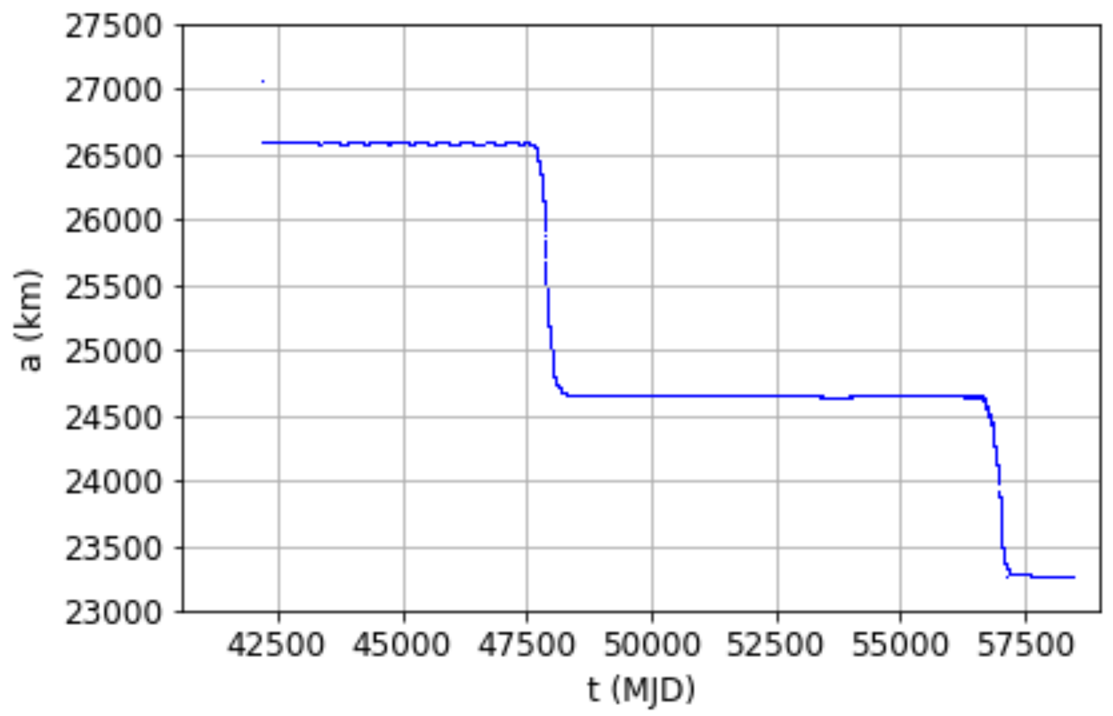
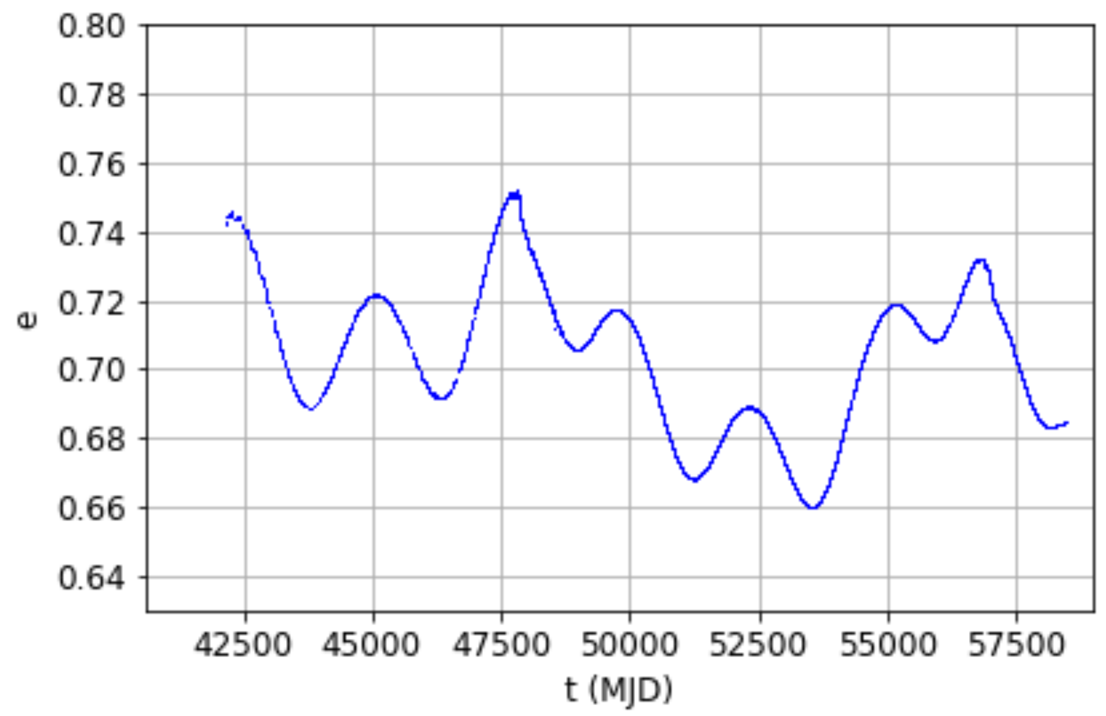
AIM

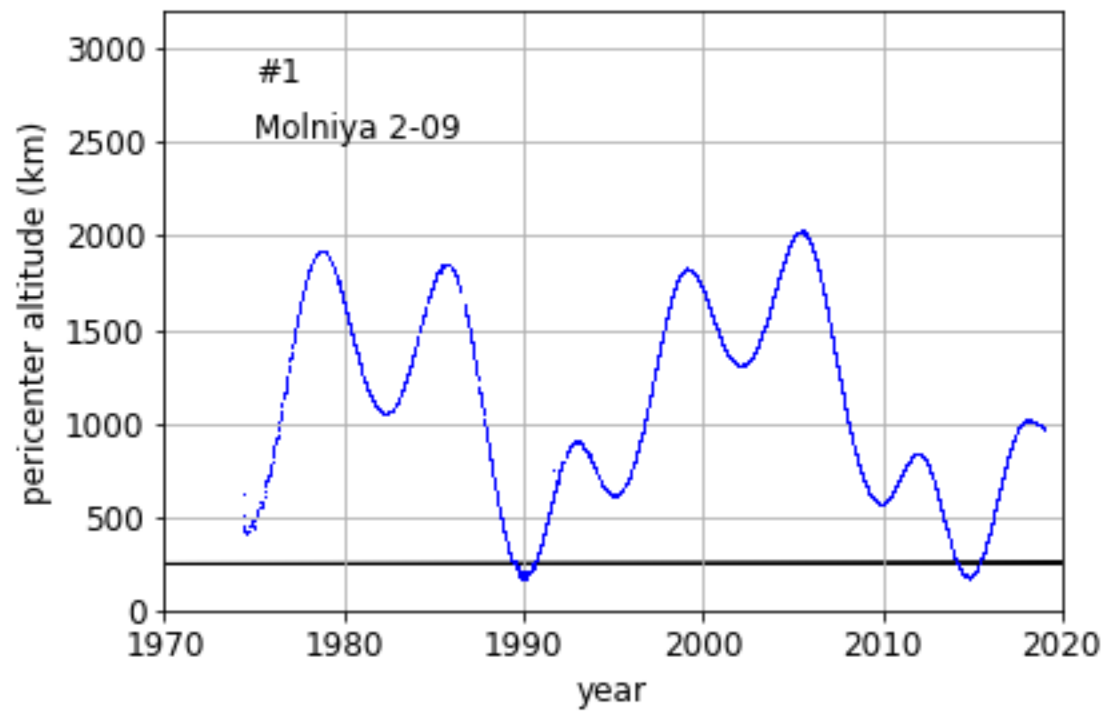
The behavior in eccentricity and semi-major axis of 42 TLE sets was analyzed in order to:

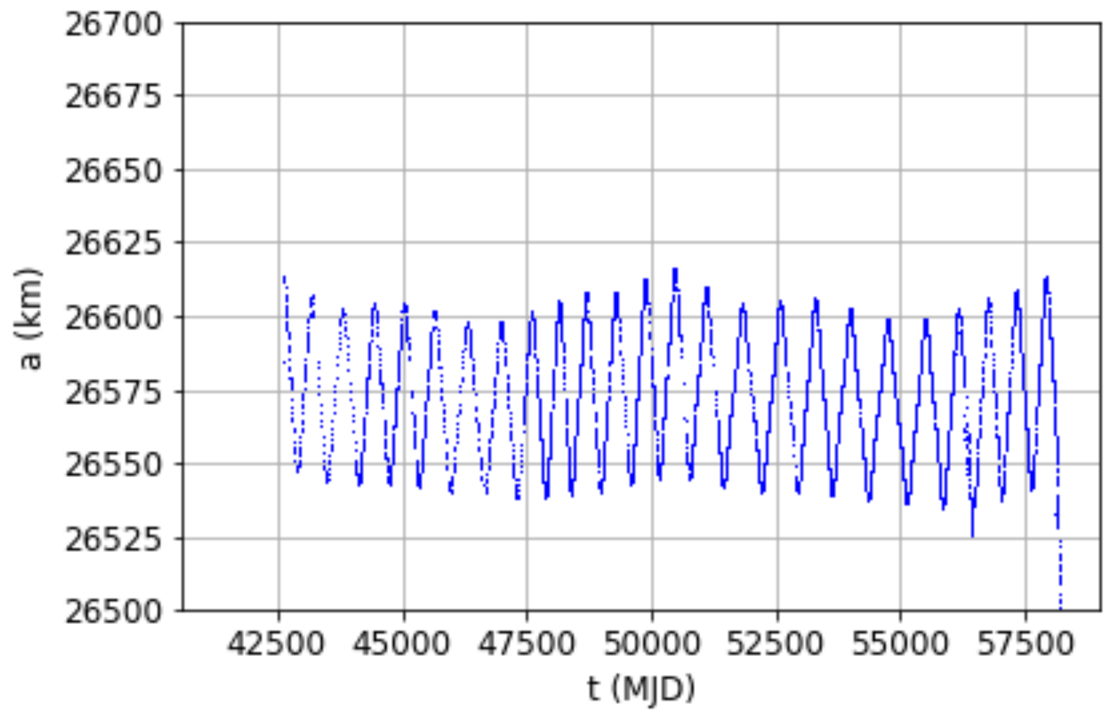
- **get some of the main dynamical features of the orbits in the long term**
- **test different tools:**
  - hierarchy of dynamical models
  - numerical propagation
  - phase space portraits
  - frequency analysis
- **looking for a synergy between the pseudo-observational data and a natural perturbation approach**

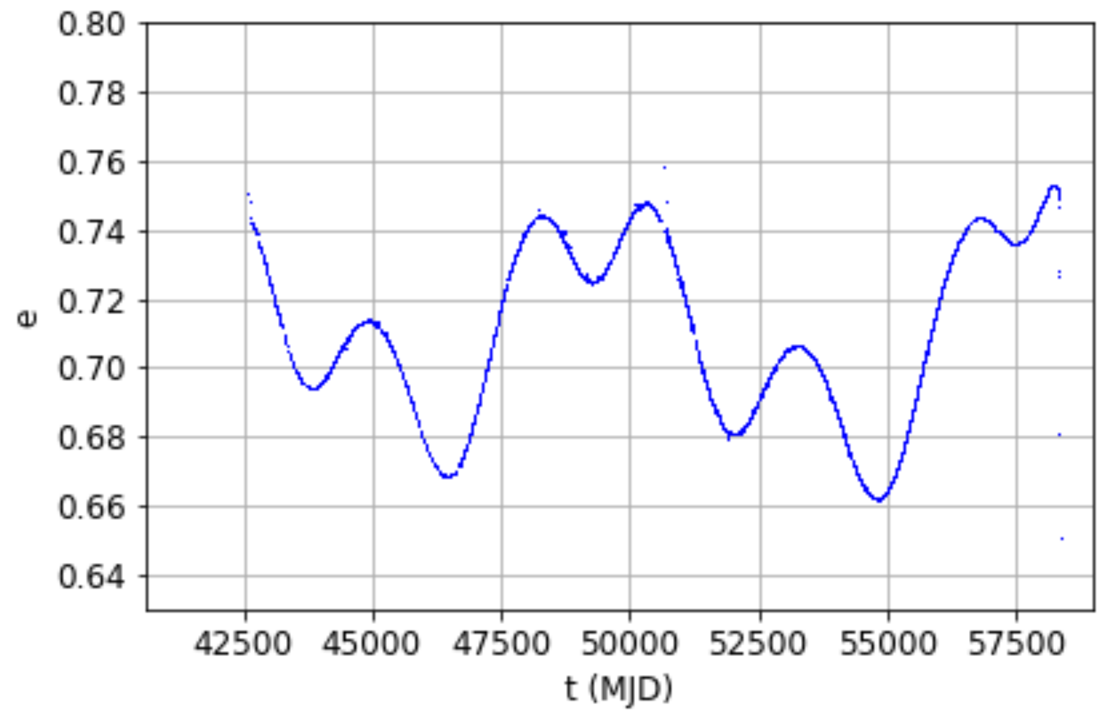
EVOLUTION GIVEN BY THE TLEs

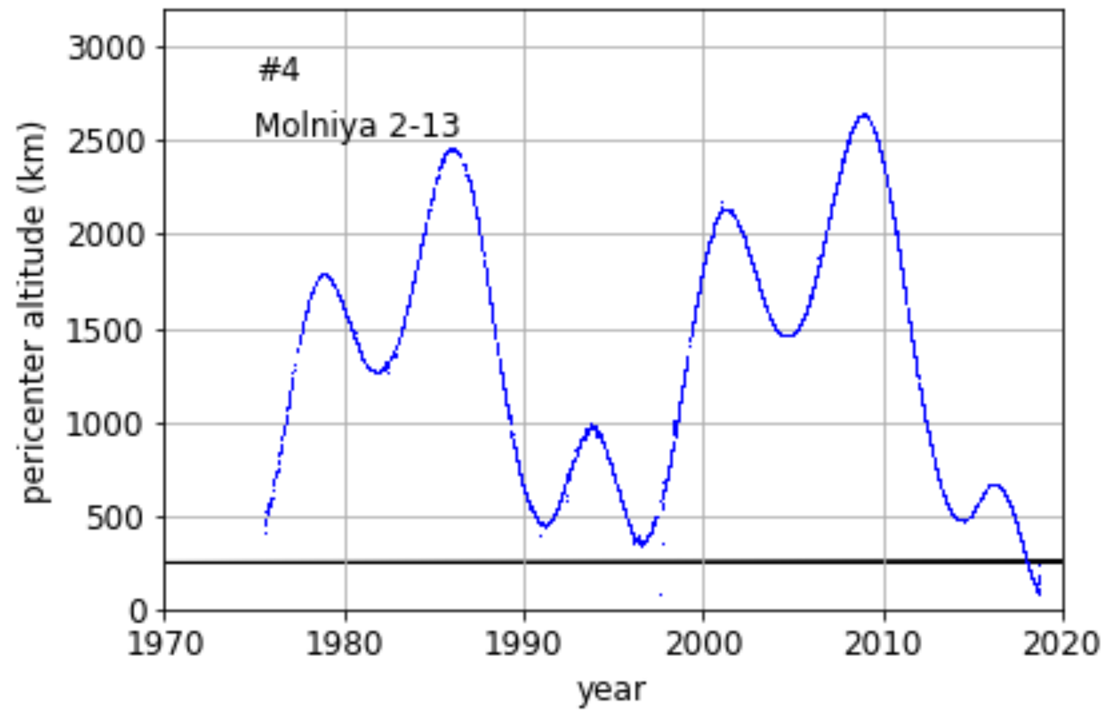






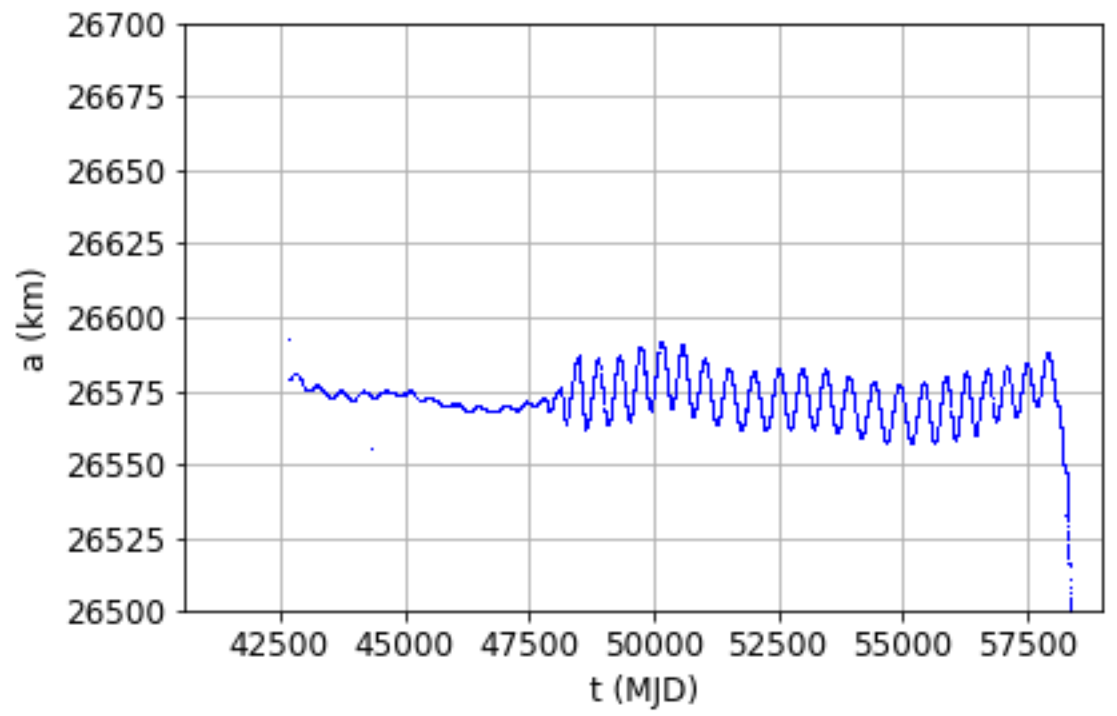


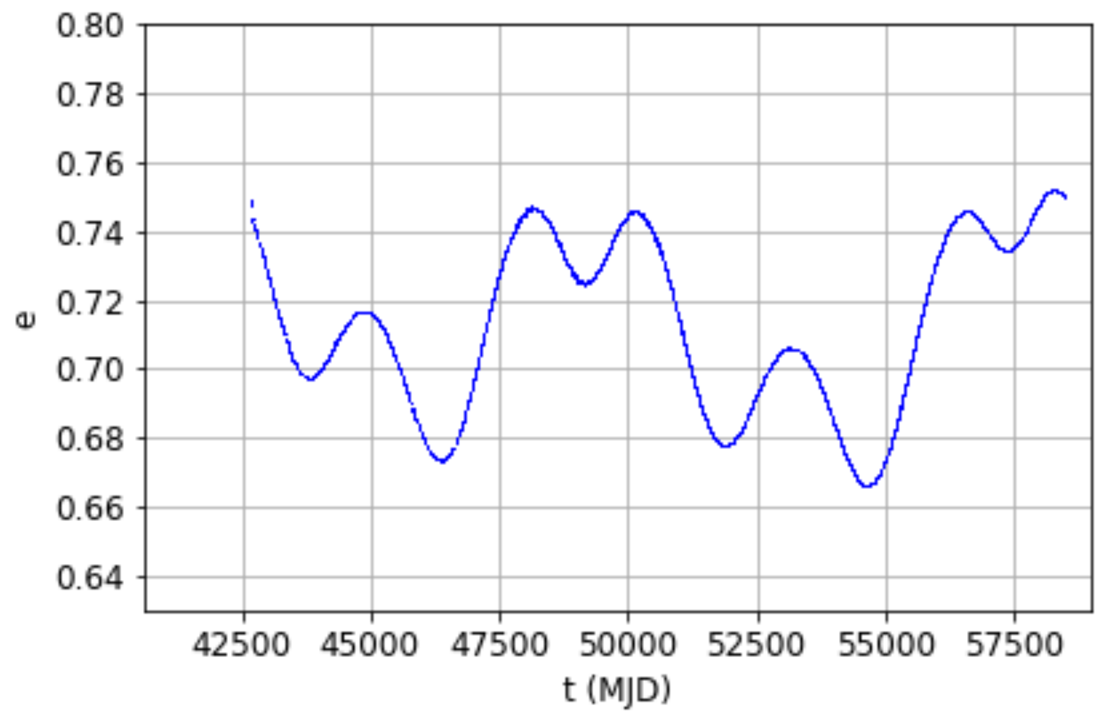


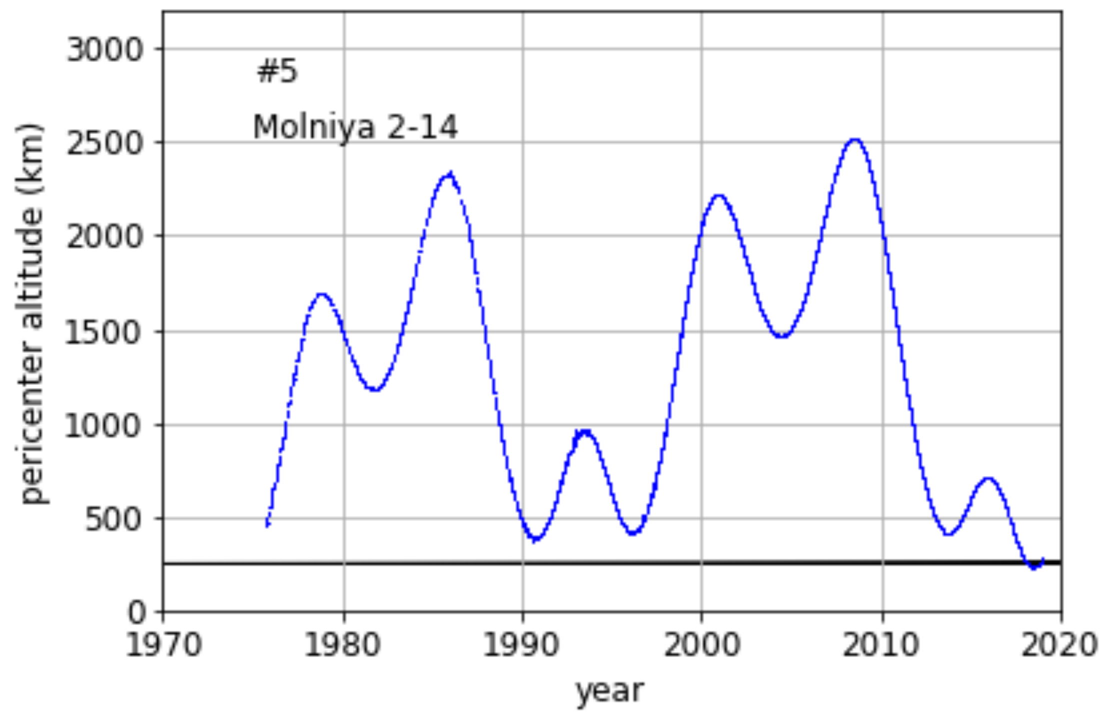


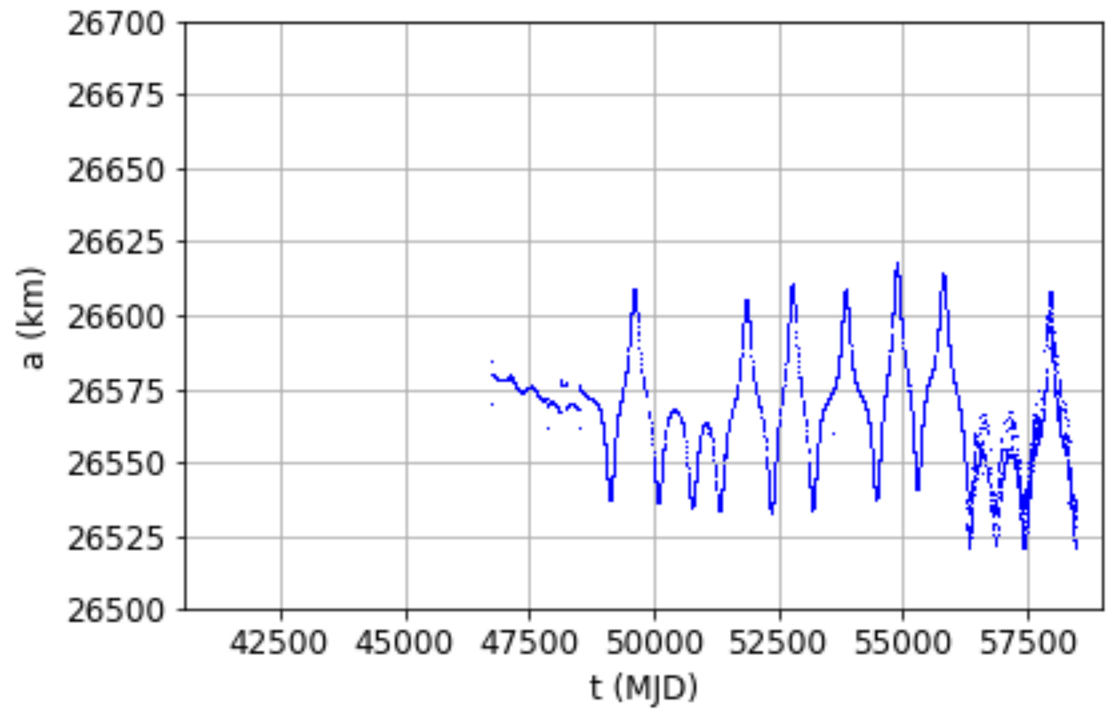
semi-major axis **eccentricity** **pericenter altitude**

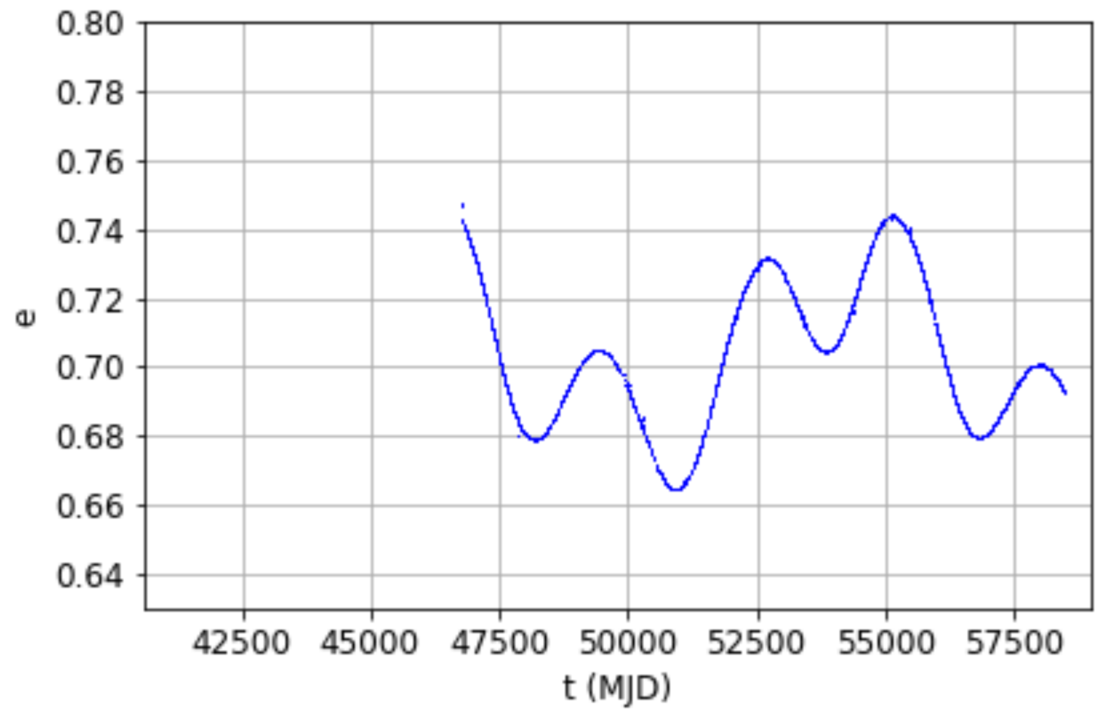
EVOLUTION GIVEN BY THE TLEs

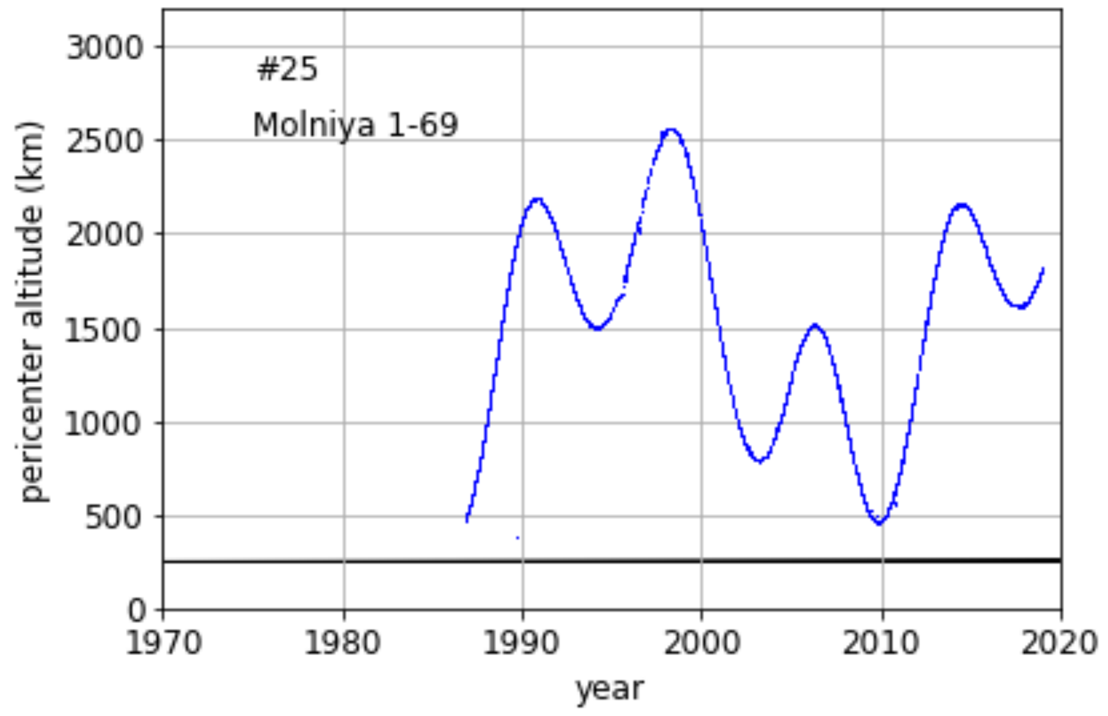












semi-major axis **eccentricity** **pericenter altitude**

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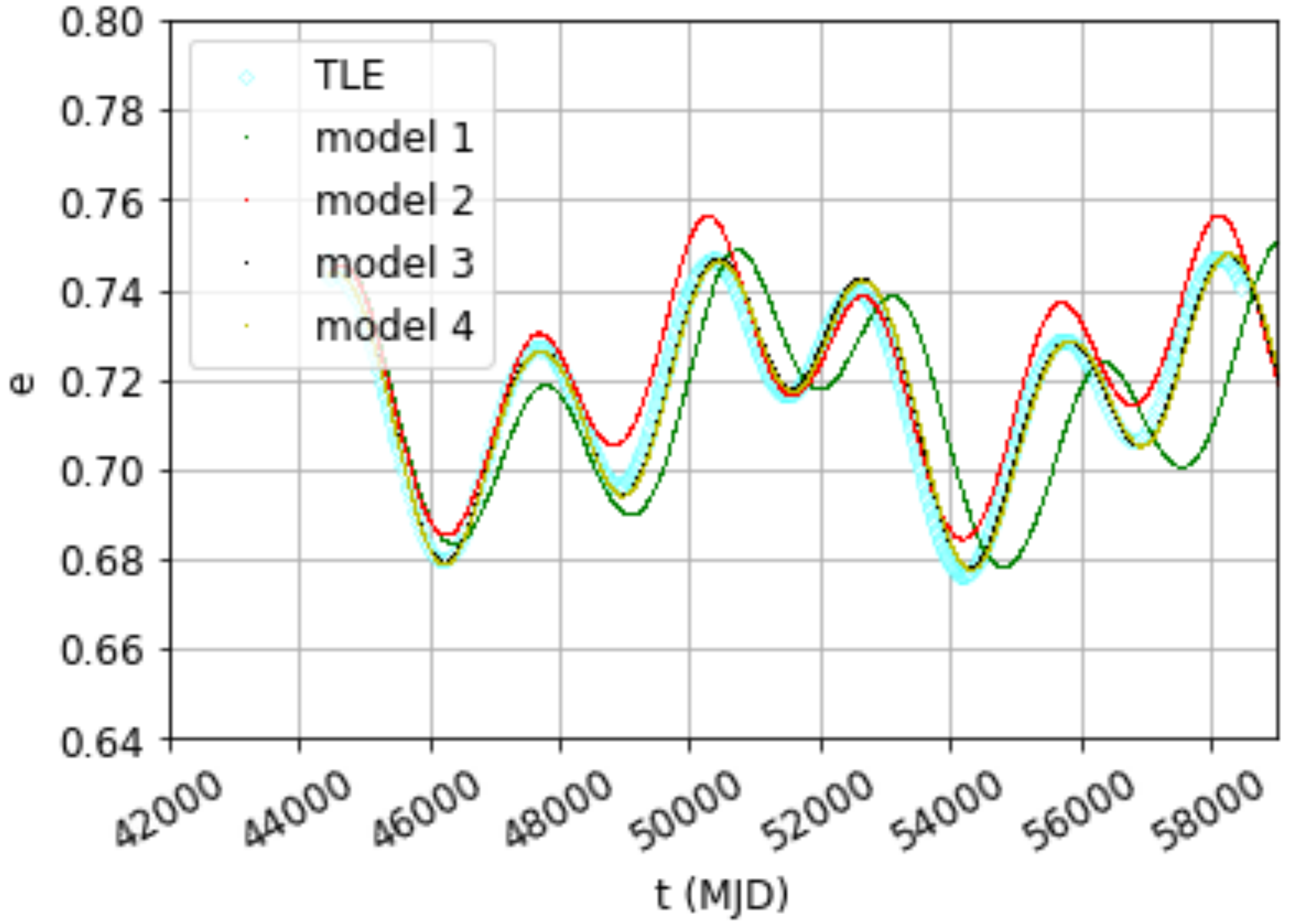
ECCENTRICITY EVOLUTION

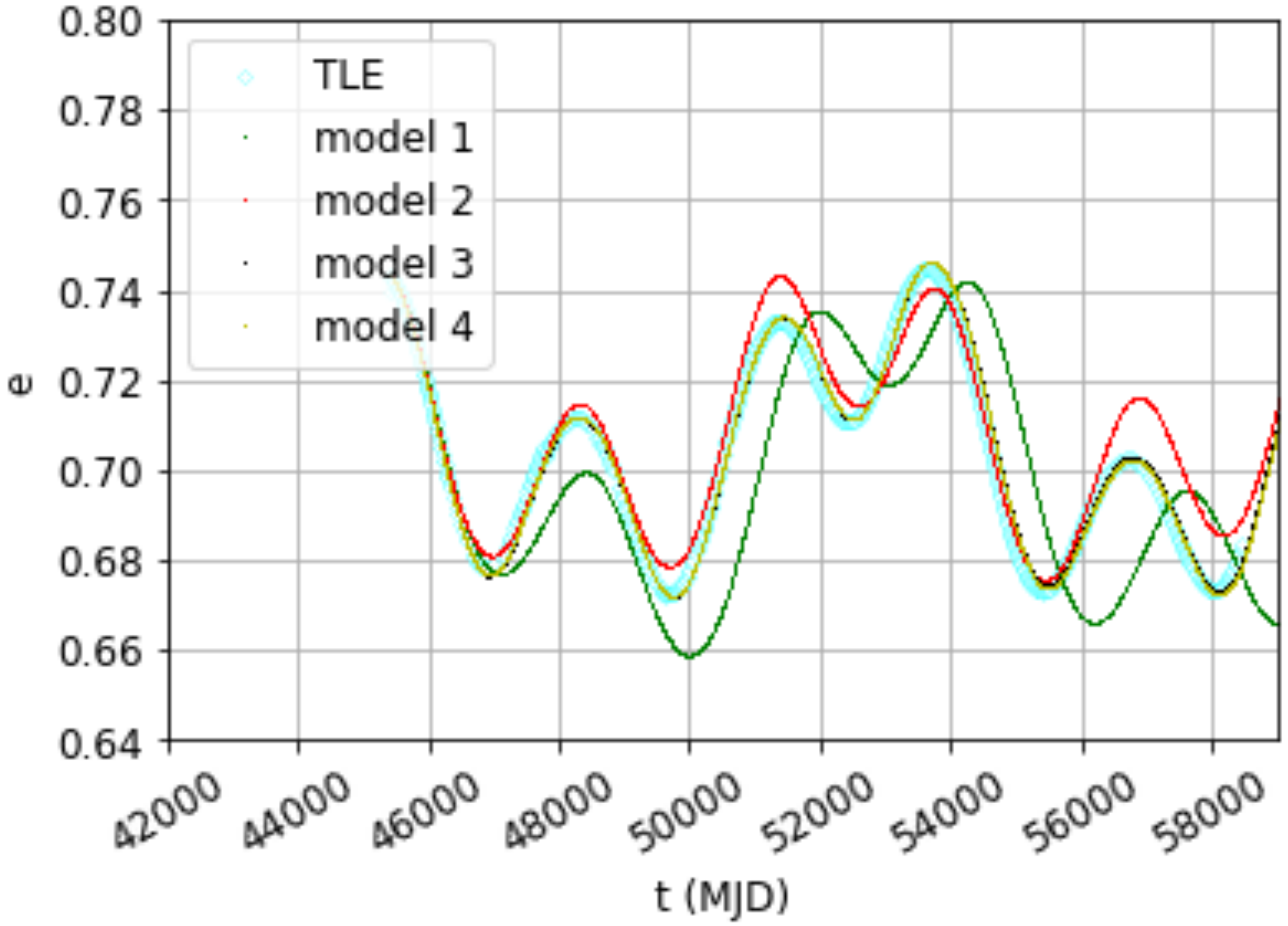
FIRST APPROACH TO TACKLE THE LONG-TERM BEHAVIOR IN ECCENTRICITY:

numerical propagation considering different models accounting only for the oblateness effect and the lunisolar perturbation

- **Doubly-averaged** approximation for the lunisolar perturbation
- Main assumption: **semi-major axis is constant**
- **Initial condition from the TLE, s.t. both $\dot{\omega}_{J_2} \approx 0$ and the 2:1 tesseral resonance are satisfied**
- Hierarchy of models

RESULTS


TLE
model 1
model 2
model 3
model 4
e
0.80
0.78
0.76
0.74
0.72
0.70
0.68
0.66
0.64
42000
44000
46000
48000
50000
52000
54000
56000
58000
t (MJD)


TLE
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0.64
42000
44000
46000
48000
50000
52000
54000
56000
58000
t (MJD)

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RESULTS

- **lunisolar perturbations must be considered for the evolution of ω and Ω**;
- if the assumption of a constant is valid within a certain limit, it turns out that only some terms of the quadrupolar approximation is enough **to follow the evolution in eccentricity**. In particular, the **following components** are mandatory
  - 2ω, $2\omega+\Omega$, $2\omega-\Omega$, Ω (Sun and Moon)
  - $2\omega-\Omega_L$, $2\omega+\Omega_L$
  - $2\omega+\Omega-\Omega_L$, $2\omega-\Omega+\Omega_L$
  - $\Omega-\Omega_L$
- Lomb-Scargle analysis has detected the following **dominant frequencies**
  - $2\dot{\omega}+\dot{\Omega}$ ($\approx$ 7 years)
  - $2\omega+\Omega_L$ ($\approx$ 25 years)
  - $2\omega+\Omega-\Omega_L$ ($\approx$ 11 years)

The dominant periodic terms can be explained looking to the ratio between the amplitude and the corresponding frequency.

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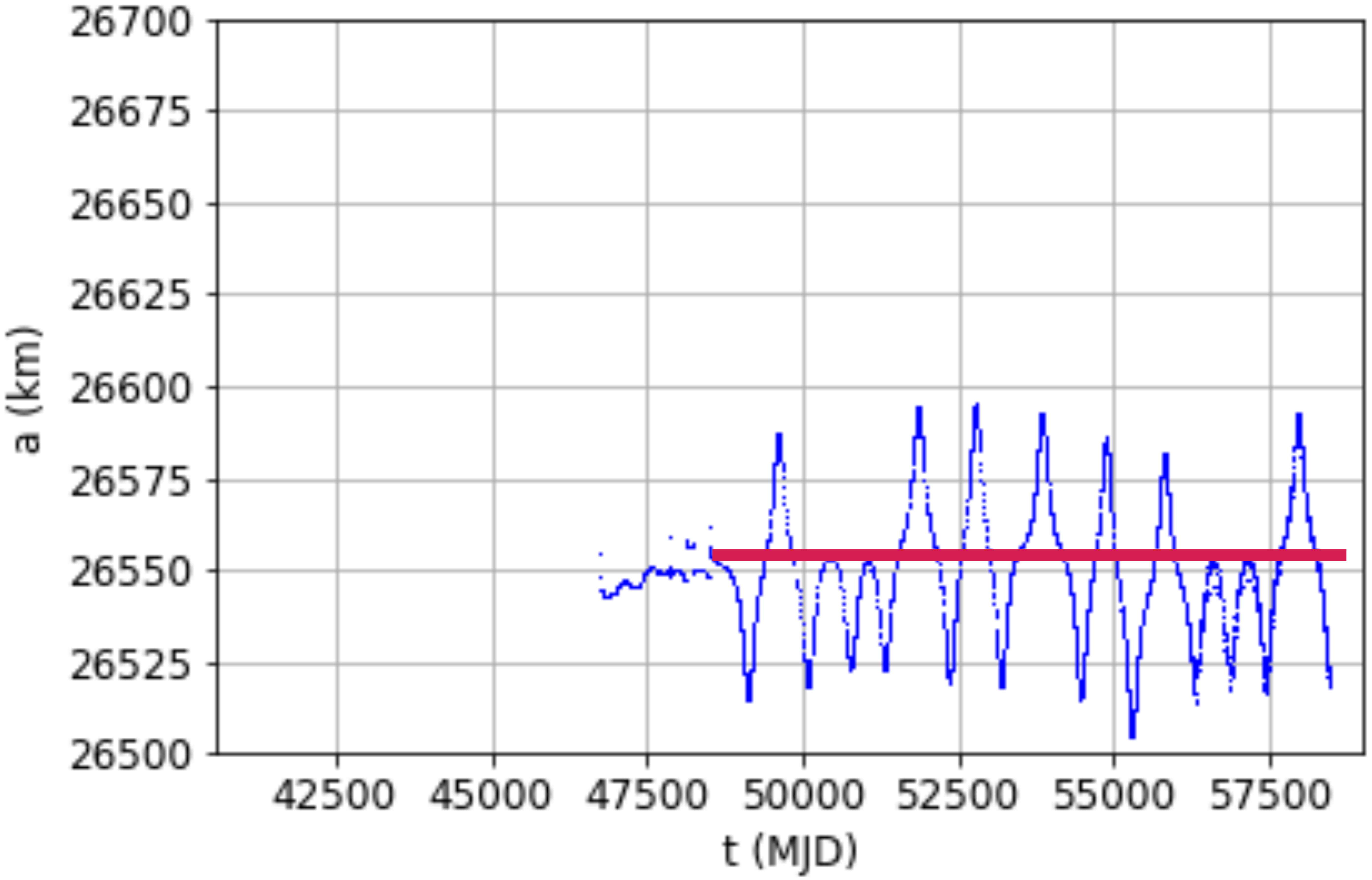
SEMI-MAJOR AXIS EVOLUTION

SEMI-MAJOR AXIS INTERMITTENCY PHENOMENON



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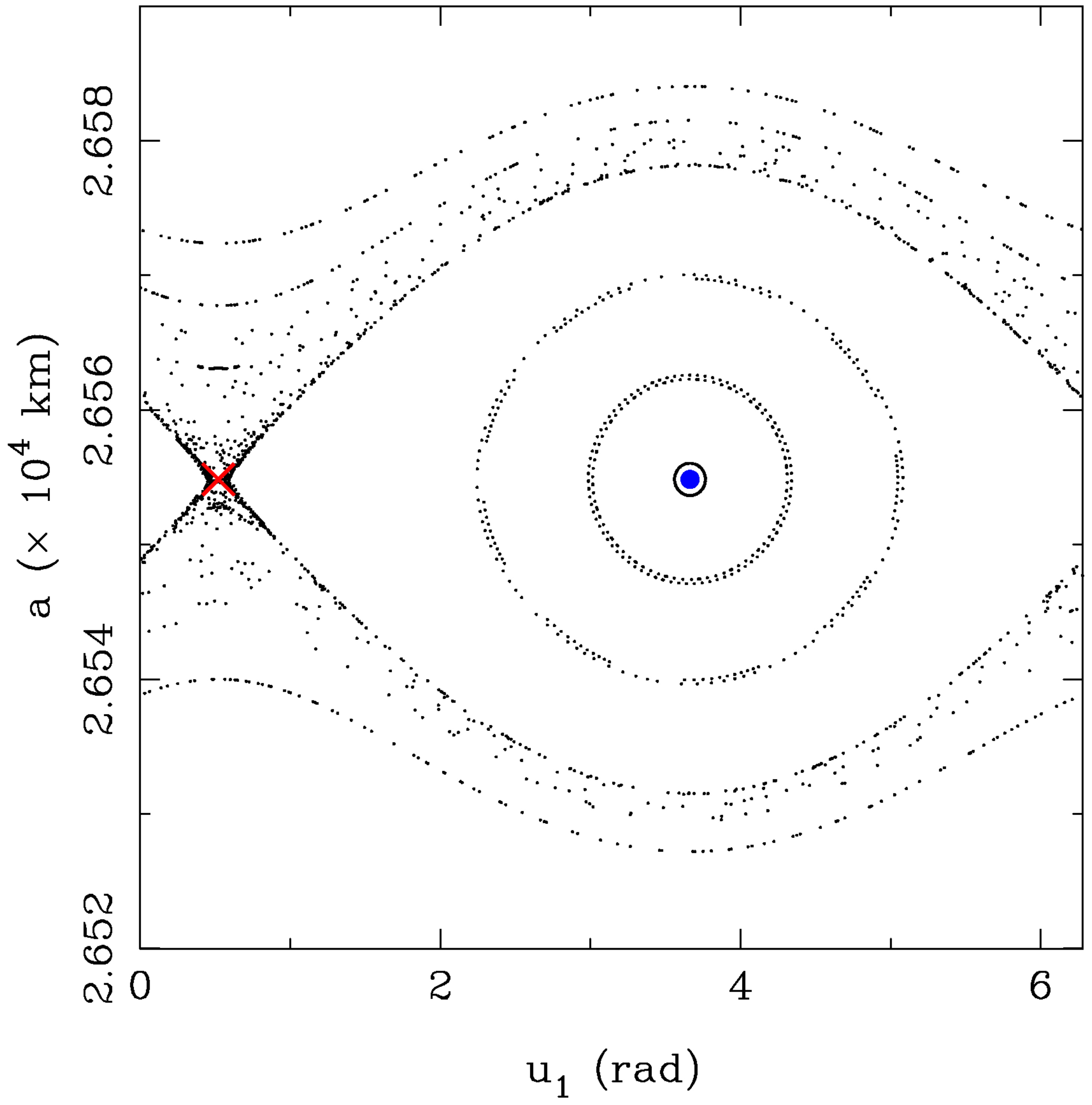
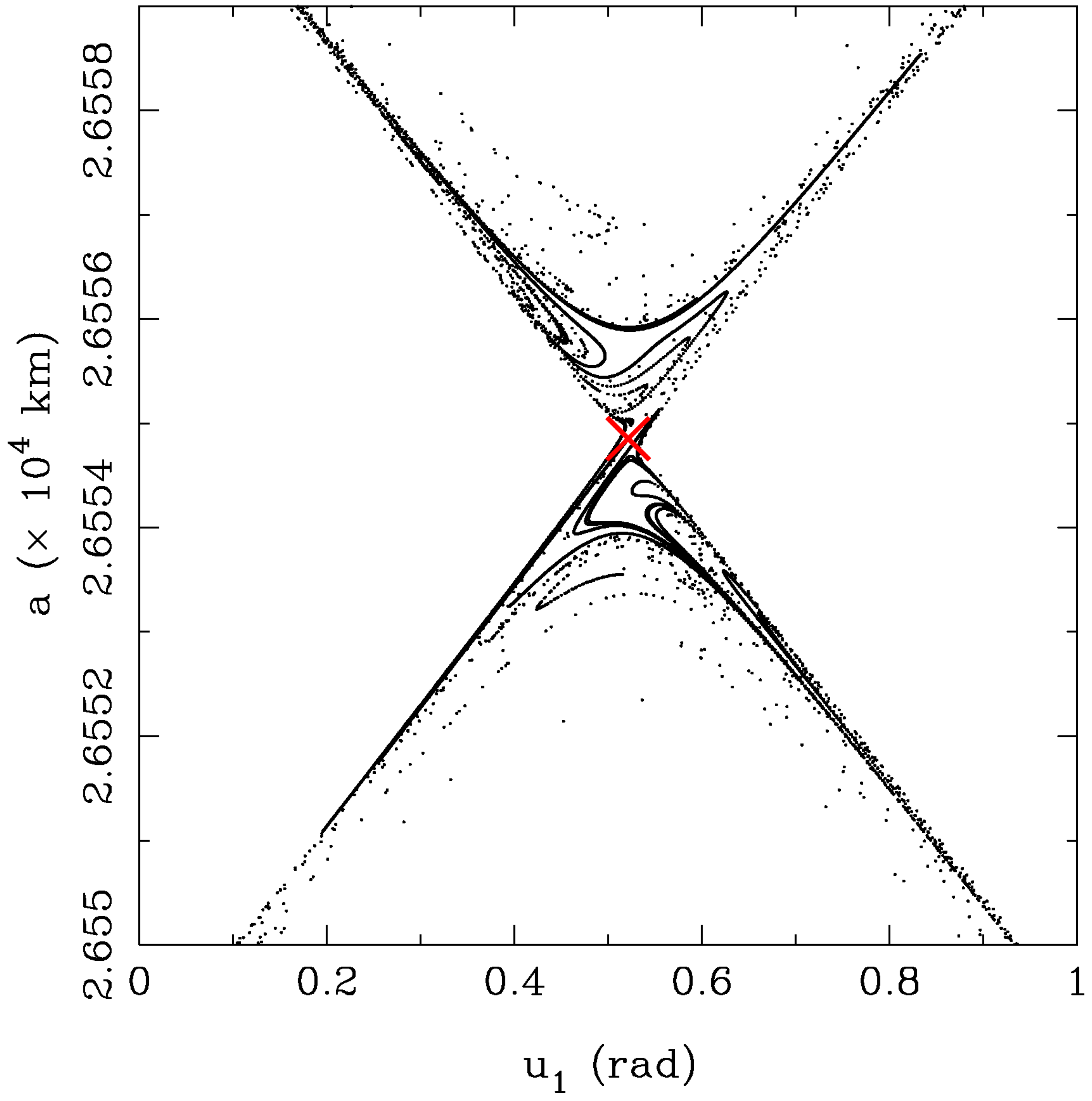
POINCARÉ SECTION

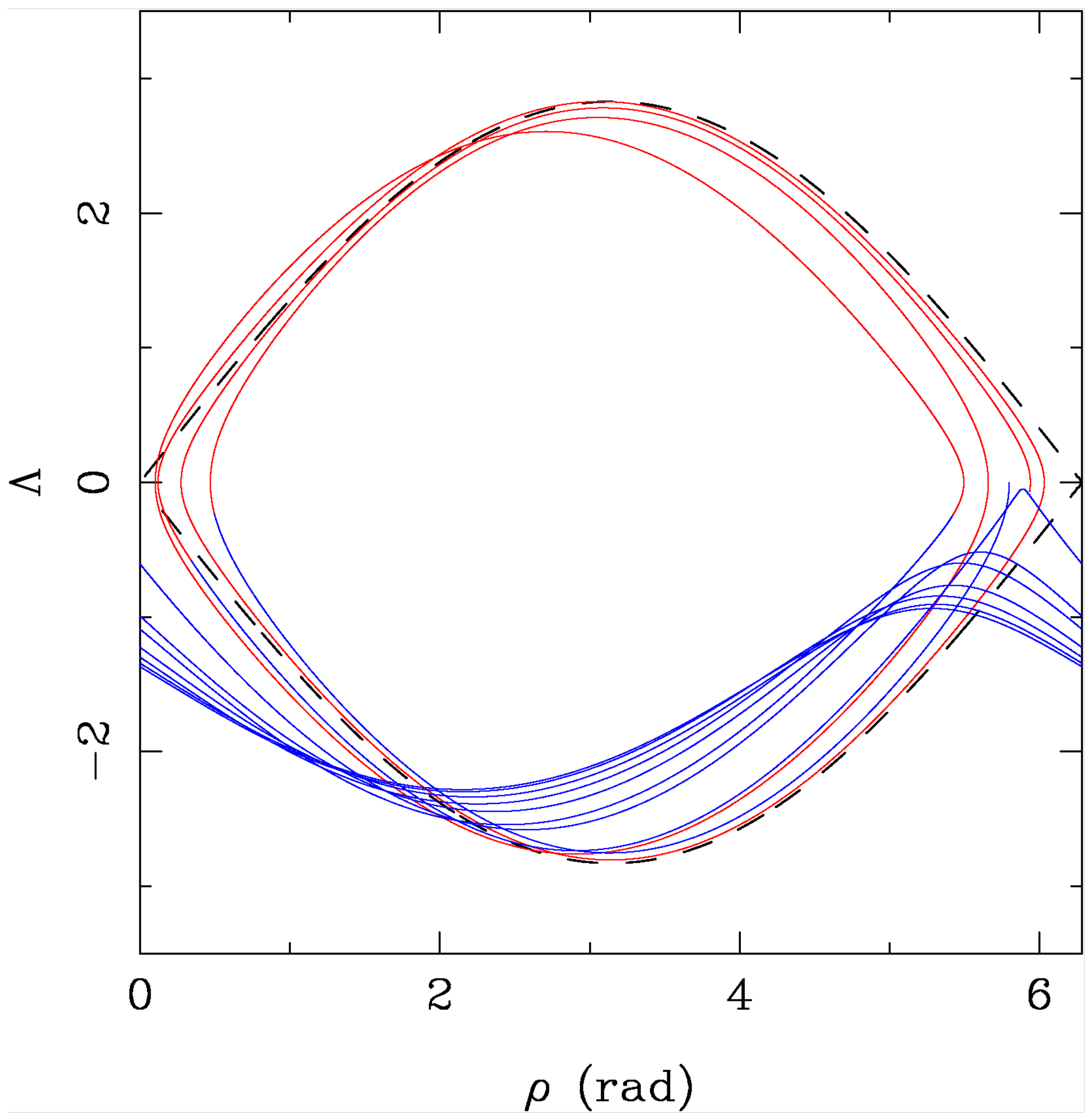


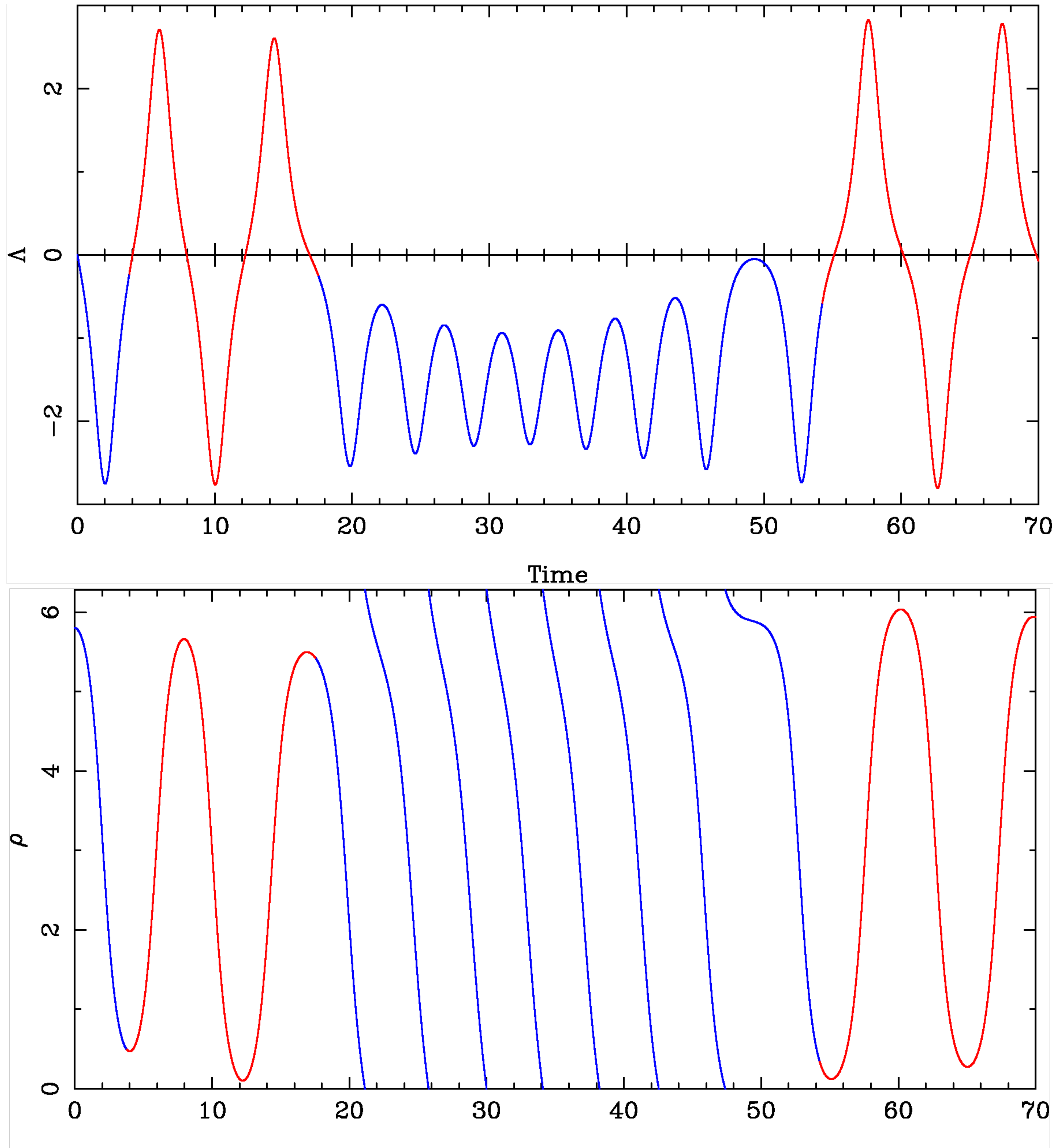


Perturbative contributions to the Hamiltonian given by the tesseral terms and the lunisolar perturbations

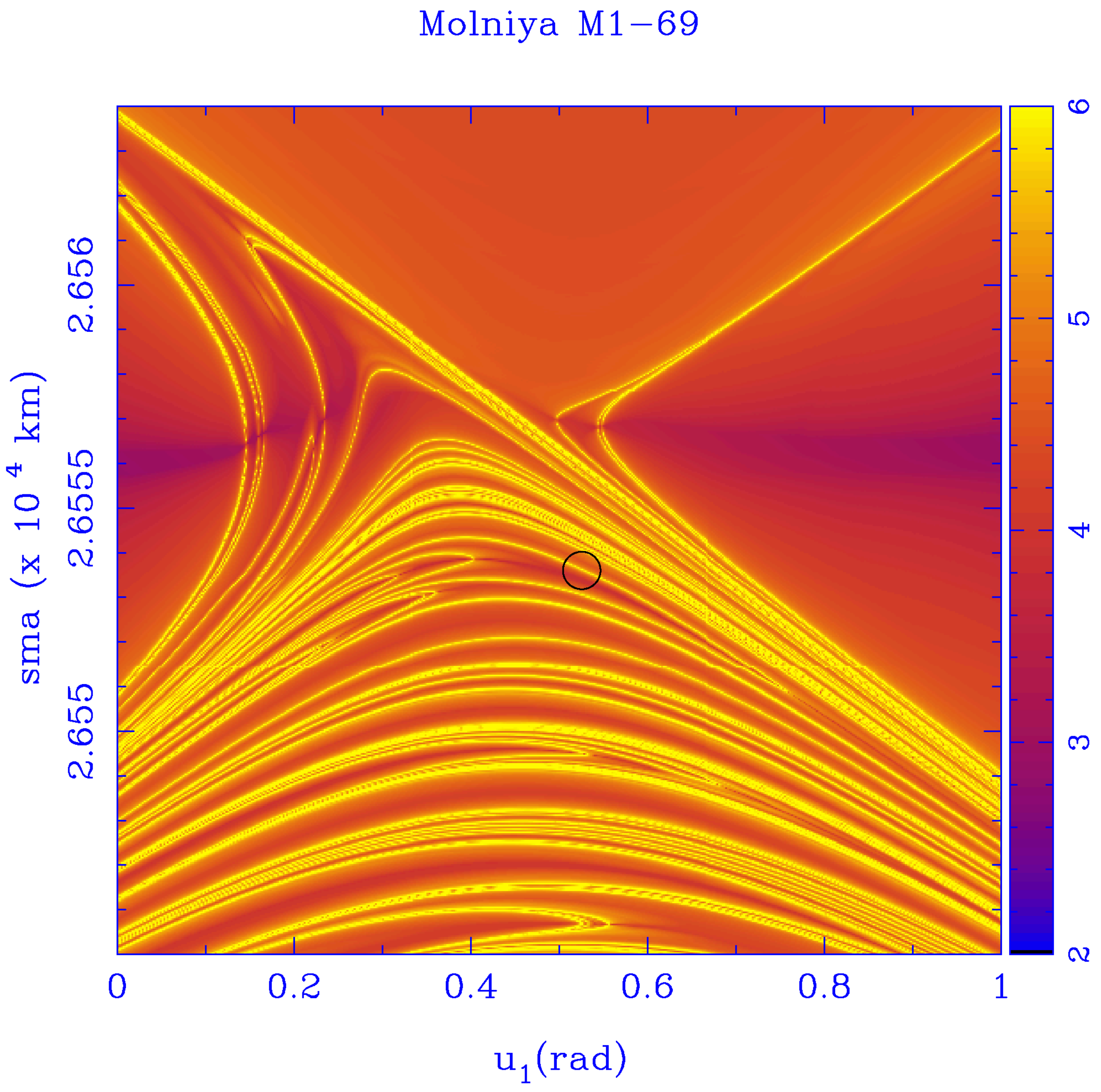
EXPLANATION OF THE INTERMITTENCY PHENOMENON

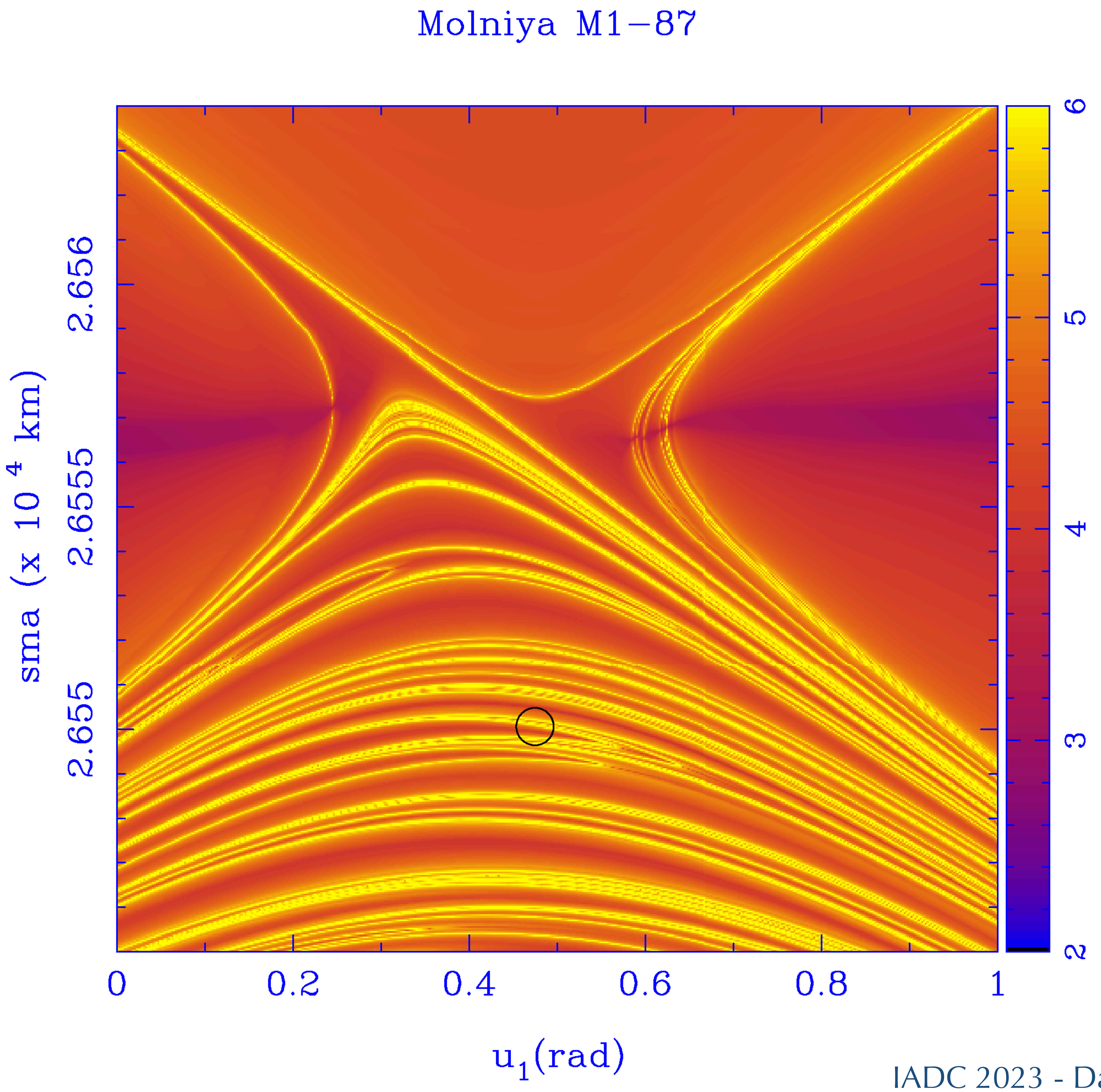
The chaotic nature close to the separatrices makes the satellite to jump from the libration to the circulation region





MOLNIYA 1-69 AND 1-87





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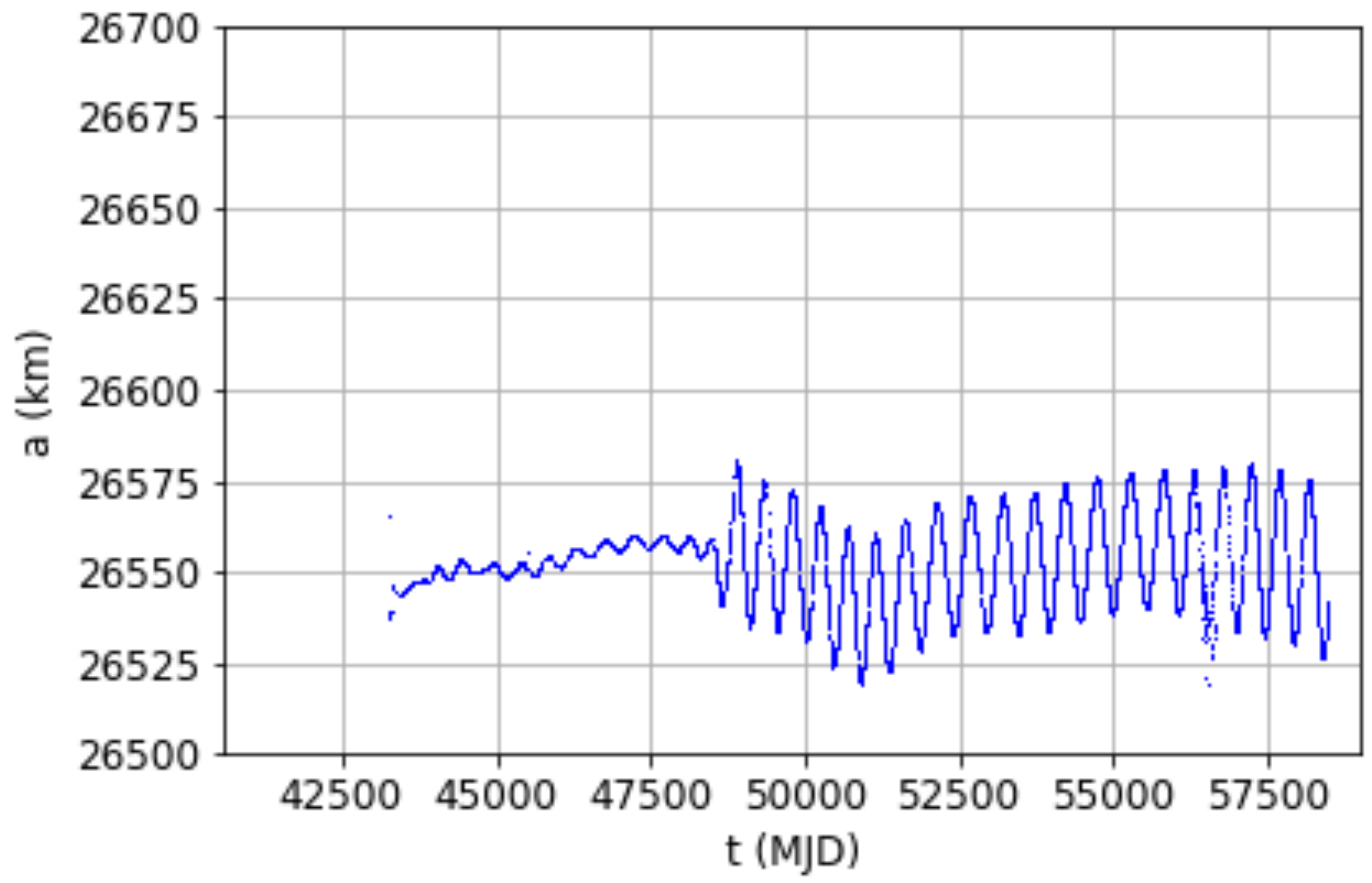
OPEN POINTS - FURTHER DEVELOPMENTS

- change of amplitudes in the periodic behavior of the semi-major axis
- chaotic behavior in eccentricity?



- **lunisolar - tesseral - drag dynamical coupling** (also, any possible data from reentry campaigns?)
- **ω drift from the critical value?**
- **long-term evolution of debris fragments?**

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PAST FRAGMENTATIONS?

TABLE 2.1 HISTORY OF SATELLITE BREAKUPS BY LAUNCH DATE (CONT'D)

Anz-Meador, P., Liou, J.C., History of On-orbit Satellite Fragmentations, 16th Edition, NASA/TP-20220019160, NASA Orbital Debris Program Office, December 2022.

SATELLITE NAME	INTERNATIONAL DESIGNATOR	US SATELLITE NUMBER	LAUNCH DATE	BREAKUP DATE	DEBRIS CATALOGED	DEBRIS LEFT	APOGEE (KM)	PERIGEE (KM)	INCLINATION (DEG)	ASSESSED CAUSE	ADDITIONAL INFORMATION
COSMOS 1278	1981-058A	12547	19-Jun-81	Dec-86	3	0	37690	2665	67.1	DELIBERATE	SELF-DESTRUCT
COSMOS 1285	1981-071A	12627	4-Aug-81	21-Nov-81	25	25	40100	720	63.1	DELIBERATE	SELF-DESTRUCT
COSMOS 1286	1981-072A	12631	4-Aug-81	29-Sep-82	2	0	325	300	65.0	UNKNOWN	COSMOS 699 CLASS
COSMOS 1305 R/B	1981-088F	12827	11-Sep-81	11-Sep-81	8	8	13795	605	62.8	PROPULSION	MOLNIYA FINAL STAGE
COSMOS 1306	1981-089A	12828	14-Sep-81	12-Jul-82	8	0	405	380	64.9	UNKNOWN	COSMOS 699 CLASS
COSMOS 1317	1981-108A	12933	31-Oct-81	25-28 Jan-84	11	11	39055	1315	62.8	DELIBERATE	SELF-DESTRUCT
METEOR 2-8	1982-025A	13113	25-Mar-82	29-May-99	53	53	960	935	82.5	UNKNOWN	
COSMOS 1348	1982-029A	13124	7-Apr-82	2-Sep-84	11	11	39200	1185	62.8	DELIBERATE	SELF-DESTRUCT
COSMOS 1355	1982-038A	13150	29-Apr-82	8-Aug-83	29	0	395	360	65.1	UNKNOWN	COSMOS 699 CLASS
COSMOS 1375	1982-055A	13259	6-Jun-82	21-Oct-85	62	59	1000	990	65.8	BATTERY	
COSMOS 1405	1982-088A	13508	4-Sep-82	20-Dec-83	32	0	340	310	65.0	UNKNOWN	COSMOS 699 CLASS
COSMOS 1408	1982-092A	13552	16-Sep-82	15-Nov-21	1760	990	490	465	82.6	COLLISION, DELIBERATE	Russian ASAT test
EKRAN 9	1982-093A	13554	16-Sep-82	23-Dec-83	1	1	35795	35788	0.7	BATTERY	
COSMOS 1423 R/B	1982-115E	13696	8-Dec-82	8-Dec-82	29	0	425	235	62.9	PROPULSION	MOLNIYA FINAL STAGE
ASTRON ULLAGE MOTOR	1983-020B	13902	23-Mar-83	3-Sep-84	1	0	1230	220	51.5	PROPULSION	PROTON-K BLOCK DM SOZ
NOAA 8	1983-022A	13923	28-Mar-83	30-Dec-85	7	1	830	805	98.6	BATTERY	
COSMOS 1456	1983-038A	14034	25-Apr-83	13-Aug-83	4	0	39630	730	63.3	DELIBERATE	SELF-DESTRUCT
COSMOS 1461	1983-044A	14064	7-May-83	11-Mar-85	189	3	890	570	65.0	UNKNOWN	COSMOS 699 CLASS

THANK YOU