ENCOUNTERS OF SMALL BODIES WITH PLANETS

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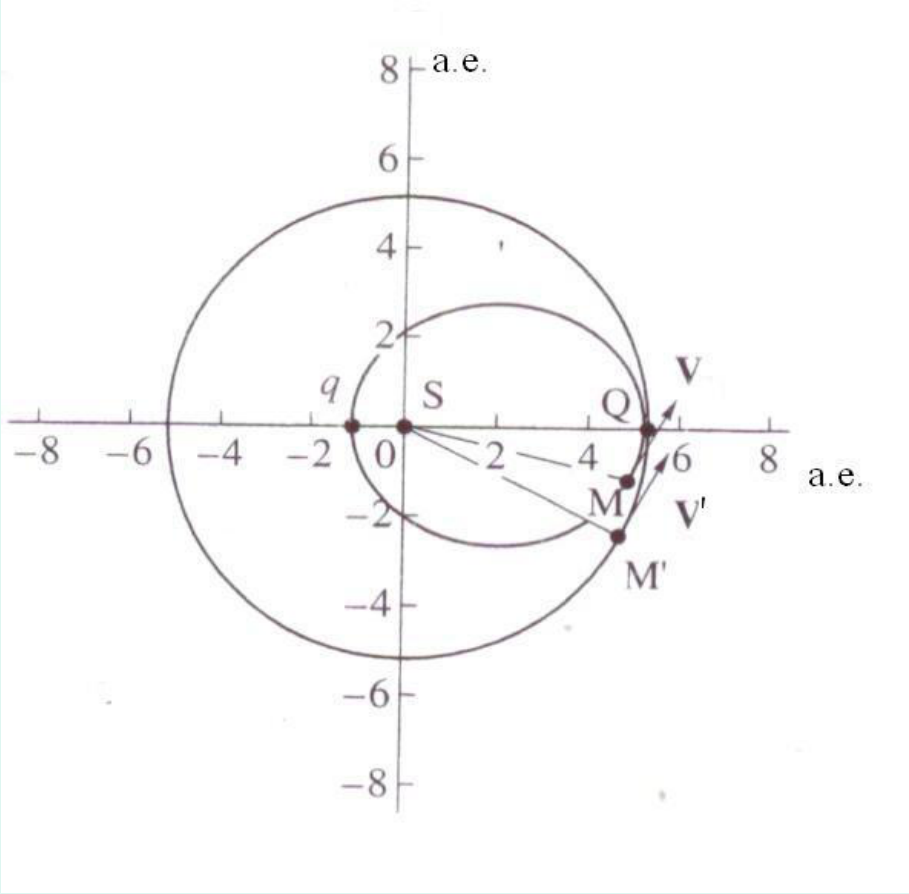
THE MAIN RESEARCH PROBLEMS

- To propose the classification of encounters by the magnitude of the planetocentric velocity: the low-velocity and the high-velocity encounters with planets.
- To propose the classification of encounters by the value of the main minimum of the planetocentric distance.
- To determine limiting sizes and shapes of orbits of small bodies with the low-velocity encounters. To map and to analyse these areas on the (a,e) plane (semimajor axis versus eccentricity).
- To determine the smallest value of the Tisserand constants for a small body relative to planets for low-velocity encounters.
- To study the low-velocity encounters of observed small bodies during encounters with Jupiter, Saturn and Earth.

CLASSIFICATION OF ENCOUNTERS BY THE PLANETOCENTRIC VELOCITY



- Low-velocity encounters

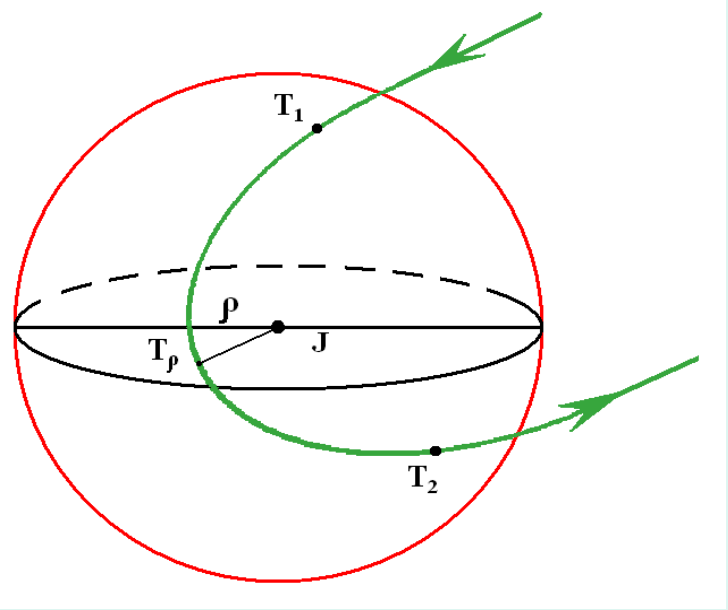
  There are low-velocity tangent segments on the orbit of a small body (i.e. there are points where heliocentric velocity vectors of the small body and the planet are equal : $\mathbf{V=V_p}$).

- High-velocity encounters

  There are no low-velocity tangent segment on the orbit of a small body.

CLASSIFICATION OF ENCOUNTERS BY A MAIN MIMIMUM OF THE PLANETOCENTRIC DISTANCE

- **Let r_G is the radius of the sphere of gravitational action of the planet.**
- **r_H - is the radius of the Hill sphere.**
- **Strong: $\rho \leq 0.5\ r_G$;**
- **close: $0.5\ r_G < \rho \leq r_H$;**
- **moderate: $r_H < \rho \leq 3\ r_H$.**
- **weak: $3\ r_H < \rho \leq 6\ r_H$.**



Table

Radii of strong, close, moderate and weak encounters of small bodies with planets (AU).

planet	strong $0{,}5r_G$	close r_H	moderate $3r_H$	weak $6r_H$
Mercury	$8 \cdot 10^{-5}$	$1{,}48 \cdot 10^{-3}$	$4{,}44 \cdot 10^{-3}$	$8{,}88 \cdot 10^{-3}$
Venus	$5{,}6 \cdot 10^{-4}$	$6{,}74 \cdot 10^{-3}$	$0{,}20 \cdot 10^{-1}$	$0{,}40 \cdot 10^{-1}$
Earth	$8{,}7 \cdot 10^{-4}$	0,01	0,03	0,06
Mars	$4{,}3 \cdot 10^{-4}$	0,007	0,022	0,043
Jupiter	0,08	0,347	1,041	2,082
Saturn	0,08	0,429	1,286	2,573
Uranus	0,006	0,465	1,395	2,79
Neptune	0,108	0,77	2,311	4,622

The duration of encounters

- Let T_1 is the moment of entry into the region of the encounter, and T_2 is the moment of exit outside the region of the encounter ($T_1 < T_2$).
- The duration of the encounter is

$$\Delta T = T_2 - T_1.$$

To determine the smallest value of the Tisserand constant for a small body relative to planets for low-velocity encounters.

- There is a criterion of the low-velocity encounters:
  - $T_P > 2.9$
- This criterion is good for small bodies in the encounters with Jupiter only.
- There are many points on the plane (a,e) that are not low-velocity points of the tangency with planets. This criterion does not work for the other planets.

Low-velocity encounters as a result of specific orbital parameters of a small body

Let us determine the orbit regions with low-velocity encounters for planets on the plane (a, e) in the pair plane problem of two bodies (ω_P)

Let r_M is the radius-vector of the low-velocity point of tangency on the small body orbit:

$$r_M = \frac{2aa_P}{a + a_P} \qquad q \le r_M \le Q$$

- **vertical borders:** **a low border:**

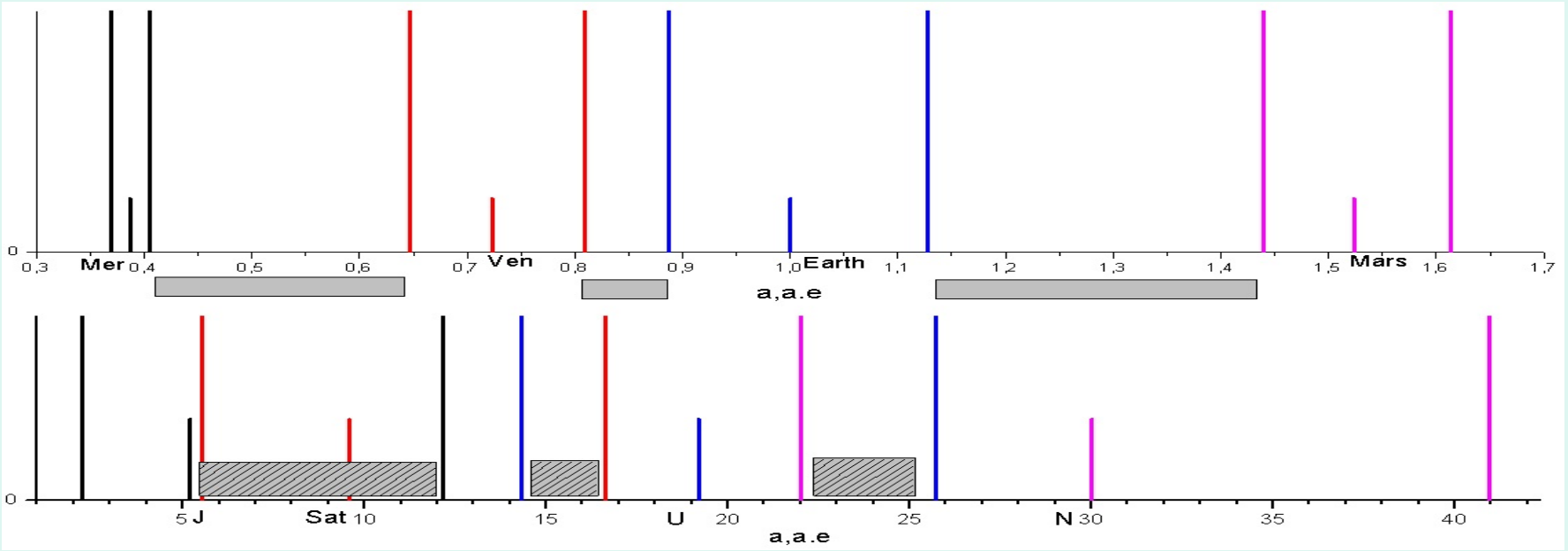
$$\frac{a_p - 6R_X^p}{a_P + 6R_X^P} a_P \le a \le \frac{a_P + 6R_X^P}{a_P - 6R_X^P} a_P \qquad \frac{|a_P - a|}{a_P + a} \le e < 1$$

Areas ω_P of the vertical borders

Planet	a_{l2}	a_{l1}	a_P	a_{r1}	a_{r2}
Mer	0.370	0.378	0.38710	0.396	0.405
V	0.647	0.684	0.72333	0.765	0.809
E	0.887	0.942	1.00000	1.062	1.128
M	1.439	1.481	1.52363	1.568	1.613
J	2.230	3.470	5.20441	7.807	12.144
Sat	5.527	7.315	9.58378	12.556	16.618
U	14.316	16.587	19.18722	22.196	25.716
N	22.010	25.729	30.02090	35.028	40.947

Analysis of the areas (ω_P) for planets of the Solar System along vertical borders

There are durations between borders of the regions (ω_P) for inner planets.



For the giant planets, the regions (ω_P) have intersections.

Upper border of the areas (ω_P)

Limiting values of the Tisserand constants for each planet in the Solar system are obtained in (Emel'yanenko N.Yu. LowSpeed Encounters as a Result of Specific Orbital Parameters of a Small Body, *Solar Syst. Res.*, 2015, v. 49, No. 6)

Upper border (ω_P)

Planet	a_P	T_{lim}	e_{min}
Mercury	0.38710	2.999	0.023
Venus	0.72333	2.997	0.056
Earth	1.00000	2.996	0.06
Mars	1.52363	2.999	0.029
Jpiter	5.20441	2.833	0.397
Saturn	9.58378	2.927	0.268
Uran	19.18722	2.979	0.145
Neptun	30.02090	2.976	0.154

The areas (ω_P) are described by:

vertical borders:

$$\frac{a_p - 6R_X^p}{a_P + 6R_X^P} a_P \leq a \leq \frac{a_P + 6R_X^P}{a_P - 6R_X^P} a_P$$

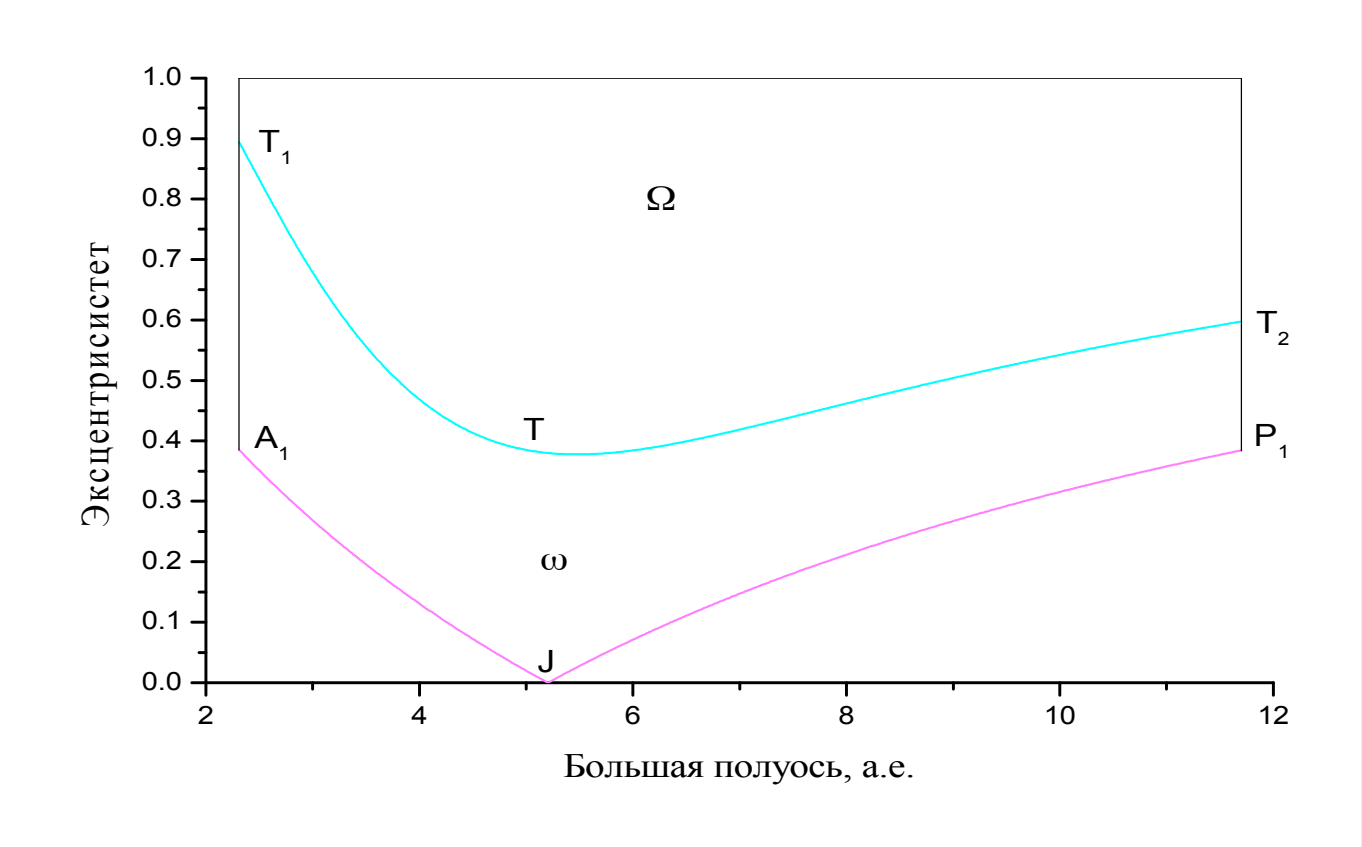
low border:

$$\frac{|a_P - a|}{a_P + a} \leq e < 1$$

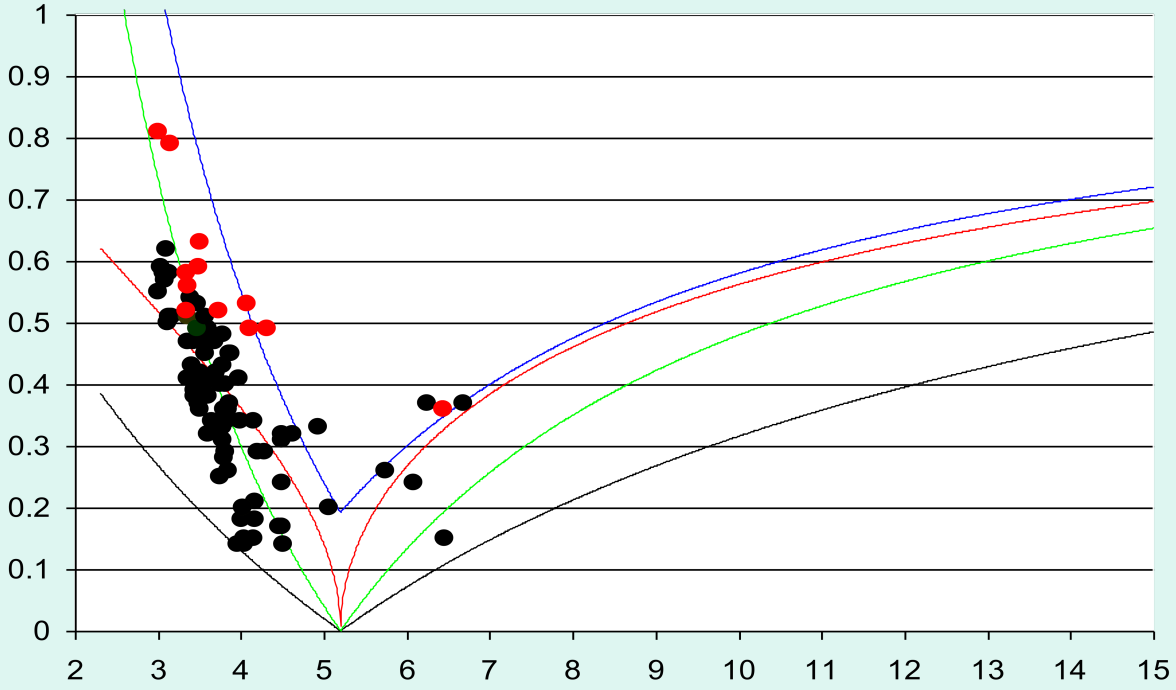
upper border

$$e \leq \sqrt{1 - \frac{a_P}{4a}\left(T_P^{\lim} - \frac{a_P}{a}\right)^2}.$$

Area (ω_J) for Jupiter:



The observed comets with low-velocities encounters with Jupiter on the plane (*a*,*e*)

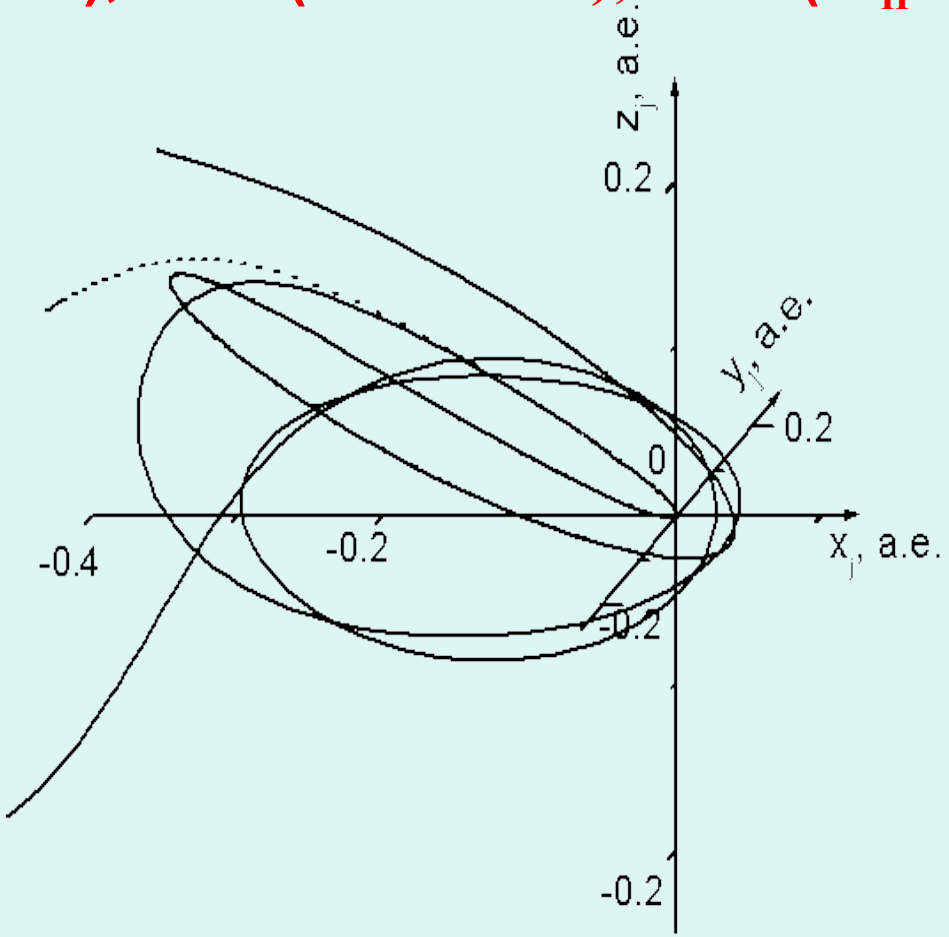


The features of encounters with Jupiter

More than two thousand encounters with Jupiter of 105 comets have been investigated.

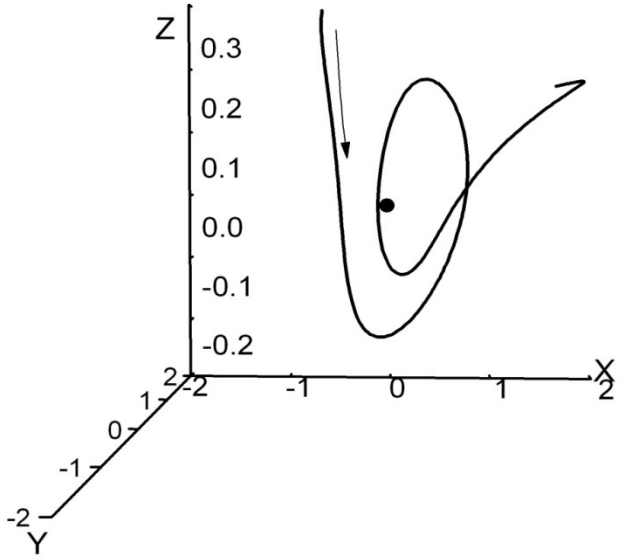
- The TSC (temporary satellite capture) occurs in 232 encounters.
- The TGC (temporary gravitational capture) into the Hill sphere occurs in 22 encounters of 10 comets.
- The FMM (physical multiple minima) occur in 13 encounters of 8 comets.

Jovicentric trajectory of Comet Gehrels 3 at the encounter with Jupiter in 1974 (phenomena: very large duration (ΔT=6230d), multiple minima (MM=4), TSC ($\Delta\tau$ =4665d), TGC (Δt_H=2960d))

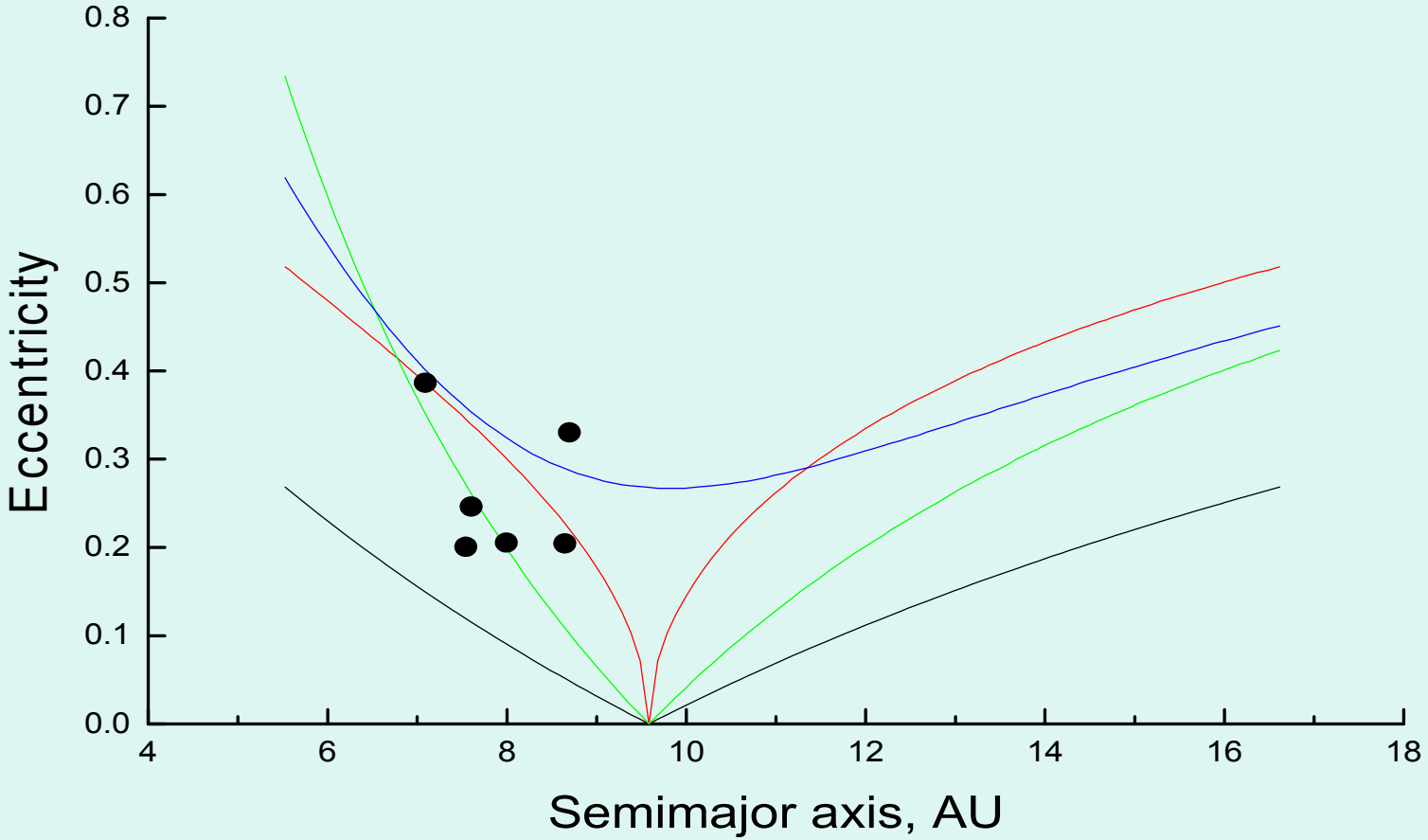


Jovicentric trajectory of Comet P/Linear-Grauer at the encounter with Jupiter in 2010

(phenomena: large duration, multiple minima (2), TSC (5.8y), TGC (1.9y))



Area ω_s. The comets with low-velocity encounters with Saturn.

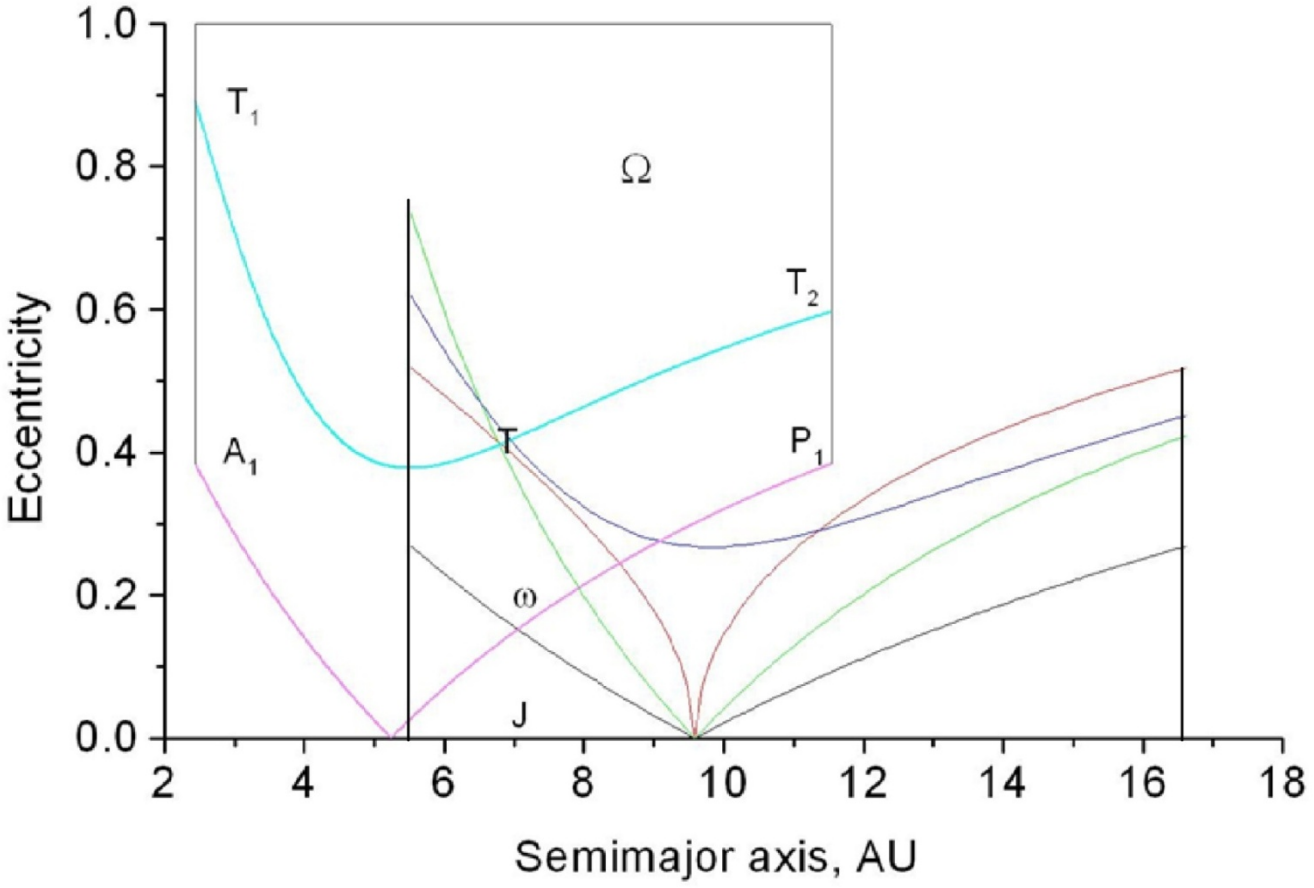


The comets with low-velocity encounters with Saturn

- P/2010 TO20 (LINEAR-Grauer) (1+1), (TGC_J), ($PhMM_J$)
- P/1997 Lagerkvist-Carsenty (1+1),
- 39P/ Oterma (1+1), (TGC_J)
- P/2005 T3 Read (1),(TSC_S)
- P/2005 S2 Skiff (2),(TSC_S), (GMM_S)
- P/2011 S1 Gibbs (2), (GMM_S)
- P/2004 A1 LONEOS (2),(TSC_S)

The area of crossing for Jupiter and Saturn

$$T_c > T_J^{\lim}, T_c > T_S^{\lim}$$



The comets with low-velocity encounters with Jupiter and Saturn

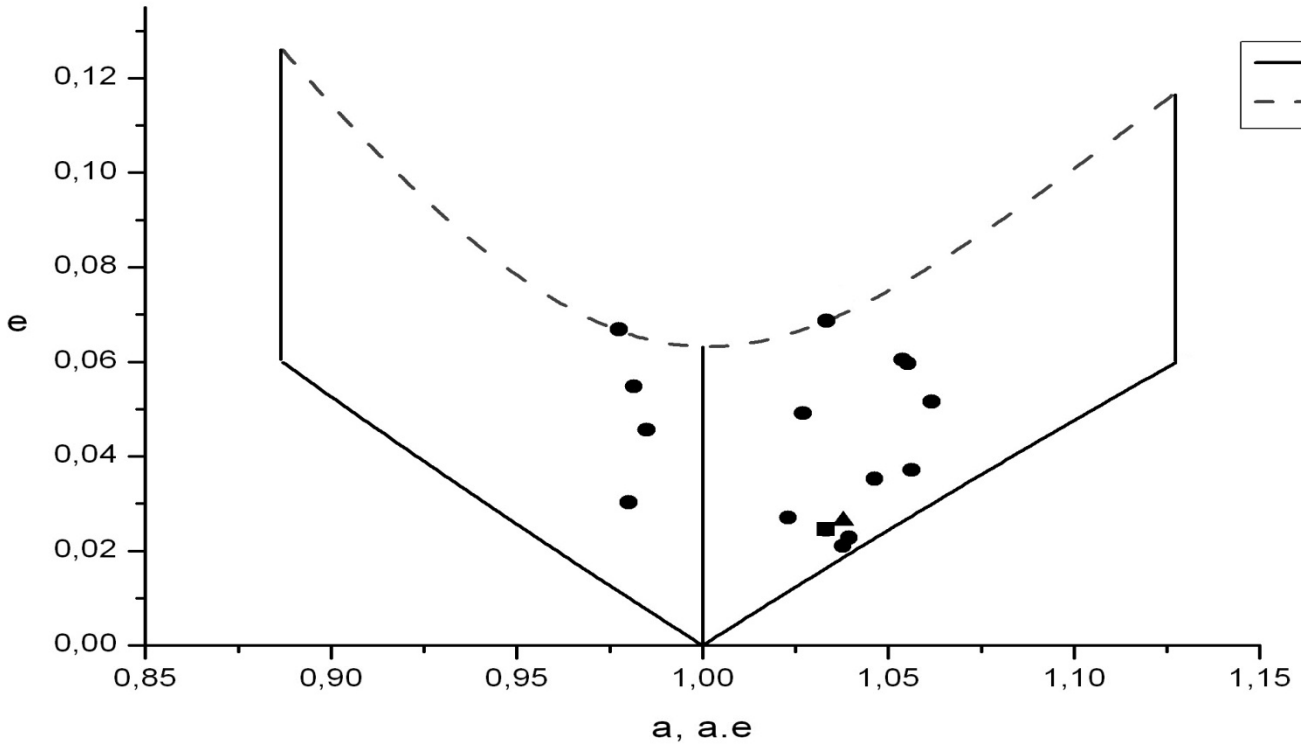
$$T_c > T_J^{\lim}, T_c > T_S^{\lim}$$

- P/2010 TO20 (LINEAR-Grauer) (1+1),
- P/1997 Lagerkvist-Carsenty (1+1),
- 39P/ Oterma (1+1).
- 82P/Gerels 3(1+1)

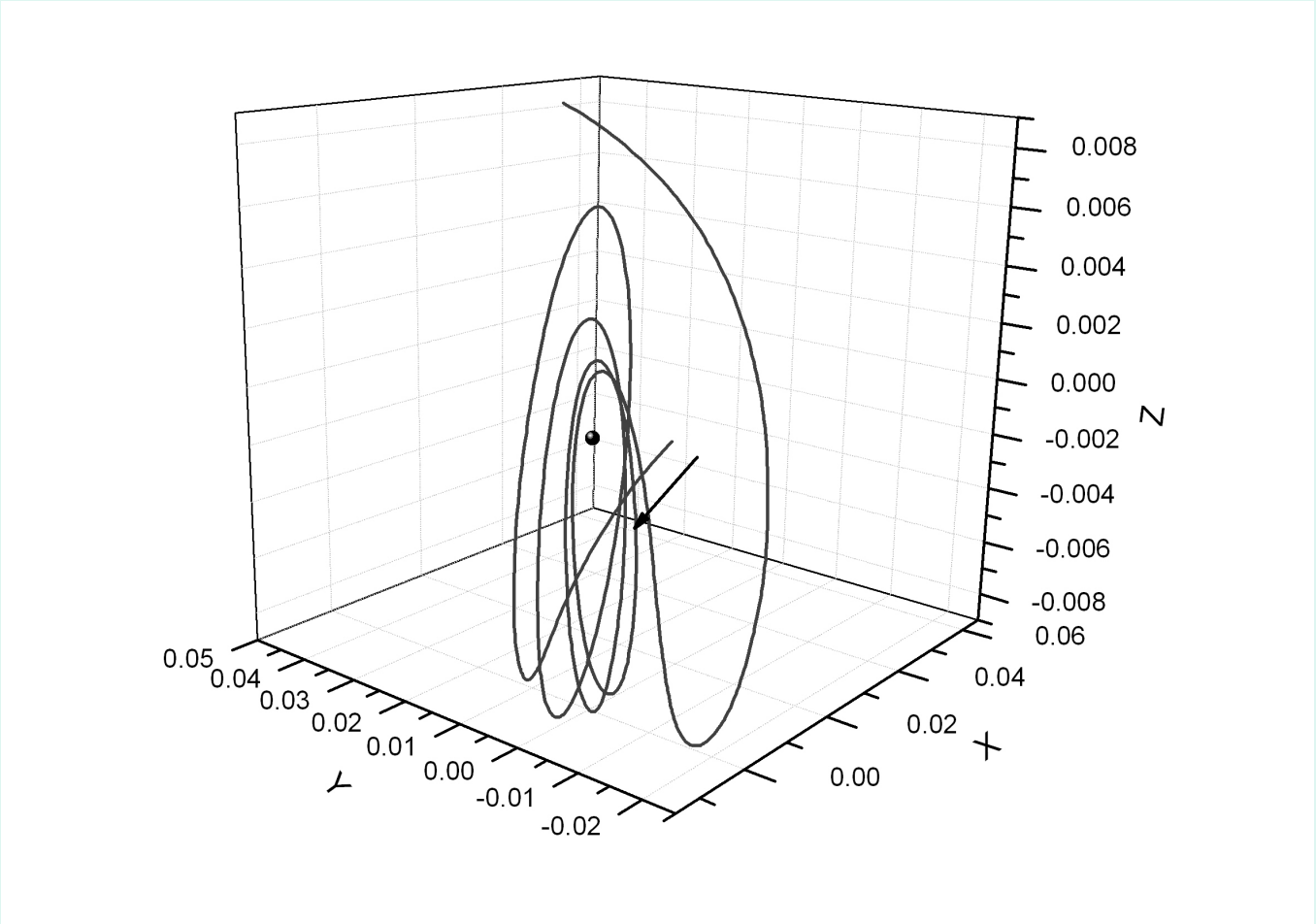
They have low-velocity encounters with Jupiter and Saturn on a small duration of time.

Area ω_E for Earth

- All 15 observed asteroids have the low-velocity encounters



Geocentric trajectory of the asteroid 2006 RH120 in 2006 (phenomena: very large duration (ΔT=657.45d), multiple minima (MM=4), TSC($\Delta\tau$=472d), TGC (Δt_H=327d))



Characteristics of Asteroid 2006 RH120

- ΔT=657.45d; $\Delta\tau$=472d; r_b=0.013AU; r_e=0.021AU; (r_{Hill}=0.01AU) Δt_H=327d.
- ρ_1= 0.0056AU; ρ_2 = 0.0036AU; ρ_3 = 0.0024AU; ρ_4 = 0.0019AU. The time durations between minima are similar: $\Delta t_{1\text{-}2}$ = 75d, $\Delta t_{2\text{-}3}$ = 81d, $\Delta t_{3\text{-}4}$ = 80d.
- Asteroid 2006 RH120 experiences TGC (temporary gravitational capture)

CONCLUSION

- In this work, the low-velocity encounters of a small body with a planet are treated as a consequence of specific size and shape of the orbit of the body. The areas of orbits are found on the plane (*a*,*e*) corresponding to the low-velocity encounters with planets.
- The limiting values of the Tisserand constant relative to a planet are determined for the low-velocity encounters.
- Observable small bodies (asteroids and comets in the areas ωJ, ωS, ωE) experiencing low-velocity encounters with planets are found.
- In encounters with Jupiter, Saturn and Earth, the Everhart-type temporal satellite captures and multiple geometrical minima (GmMM) of planetocentric distance are observed.

- The TGCs into the Hill sphere occur in 20 encounters with Jupiter and one encounter with Earth.
- Multiple physical minima (MPM) of planetocentric distance occur in 14 encounters with Jupiter and in one encounter with the Earth.
- The information about MGM and MPM is presented in (Emel'yanenko, 2012).
- It has been shown that the selection criteria of orbits used for small bodies-candidates for low-velocity encounters with planets according to the Tisserand constant are less accurate than the criteria proposed in this work.

Thank you for your attention!

The used Papers

- Emel'yanenko N.Yu., The dynamics of cometary orbits in close encounters with Jupiter. An analysis of encounter durations, *Solar Syst. Res.*, 2003, v. 37, no. 2.
- Emel'yanenko N.Yu., The dynamics of cometary orbits in close encounters with Jupiter. Kinematiks of low-velosity encounters, *Solar Syst. Res.*, 2003, v. 37, no. 2.
- Emel'yanenko, N.Yu., Orbital evolution of short period comets with high values of the Tisserand constant, *Proc. IAU Symp. Near Earth Objects, Our Celestial Neighbors: Opportunity and Risk*, 2007, no. 236.
- Emel'yanenko, N.Yu., Asteroids with high Tisserant constant with respect to major planets, *Tr. Mezhd. konf. "Okolozemnaya astronomiya2009"* (Proc. Int. Conf. "Circumterrestrial Astronomy"), Kazan, 2009.
- Emel'yanenko, N.Yu., Temporary satellite capture of comets by Jupiter, *Solar Syst. Res.*, 2012, v. 46, no. 3.
- Emel'yanenko N.Yu. LowSpeed Encounters as a Result of Specific Orbital Parameters of a Small Body, *Solar Syst. Res.*, 2015, v. 49, no. 6.
- Emel'yanenko N.Yu. Features of Encounters of Small Bodies with Planets, *Solar Syst. Res.*, 2015, v. 49, no. 6.

CLASSIFICATION OF ENCOUNTERS BY A MAIN MIMIMUM OF THE PLANETOCENTRIC DISTANCE

- **The encounter is called strong if a small body falls into the sphere with a radius of**

$$\rho \le 0.5\, r_G$$

where r_G is the radius of the sphere of gravitational action of the planet.

- **The encounter is called close if a small body passes outside this sphere but inside the Hill sphere:**

$$0.5\, r_G < \rho \le r_H\ .$$

- **The encounter is called moderate if a small body passes outside the Hill sphere but not farther than $3\, r_H$**

$$r_H < \rho \le 3\, r_H.$$

- **The low-velocity encounter is called weak in the case**

$$3\, r_H < \rho \le 6\, r_H.$$

Model A_1 (P_1)

Take the simple model of the encounter: a point of the low-velocity tangency coincides with one of the apsidals points. It lies on the border of an encounter ($6R_H$).

Formula for e:

$$e = \frac{|a_P - a|}{a} + \frac{6r_H^P}{a}$$

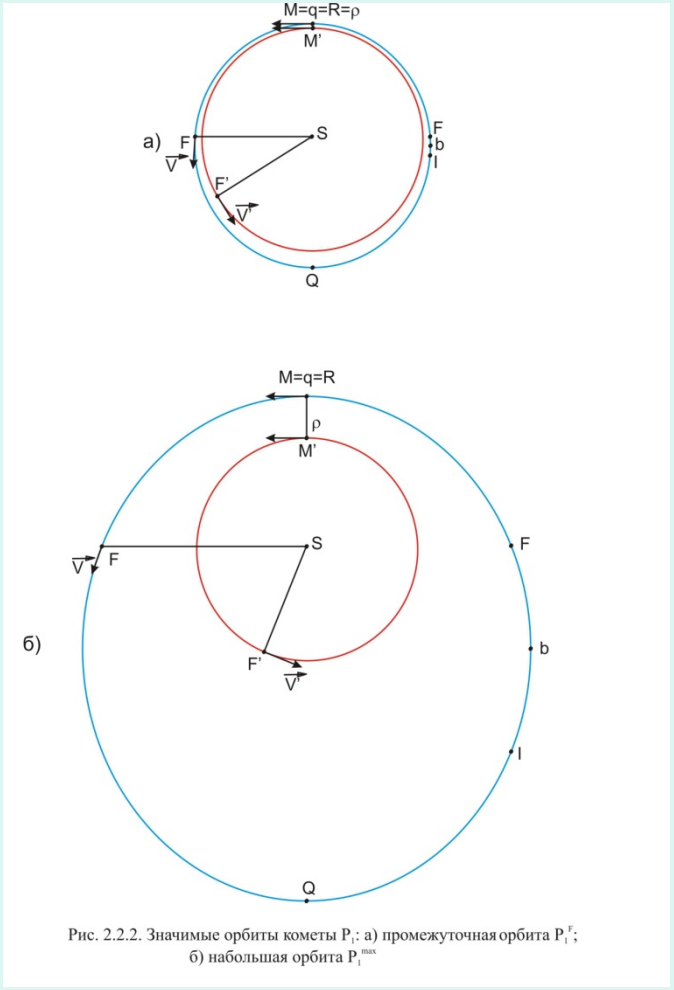
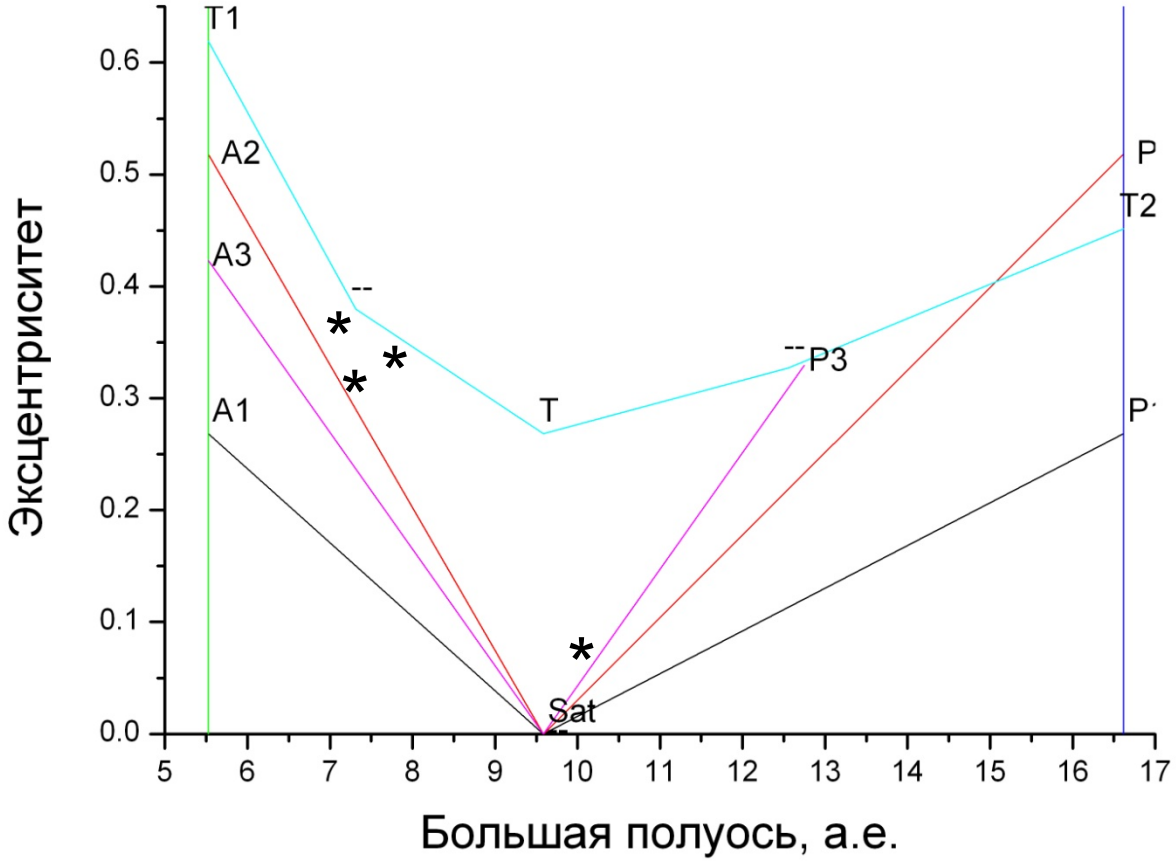


Рис. 2.2.2. Значимые орбиты кометы P_1: а) промежуточная орбита P_1^F; б) набольшая орбита P_1^{max}

Сатурн


T1
A2
A3
A1
T
P3
P
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Sat
Эксцентриситет
Большая полуось, а.е.
0.0
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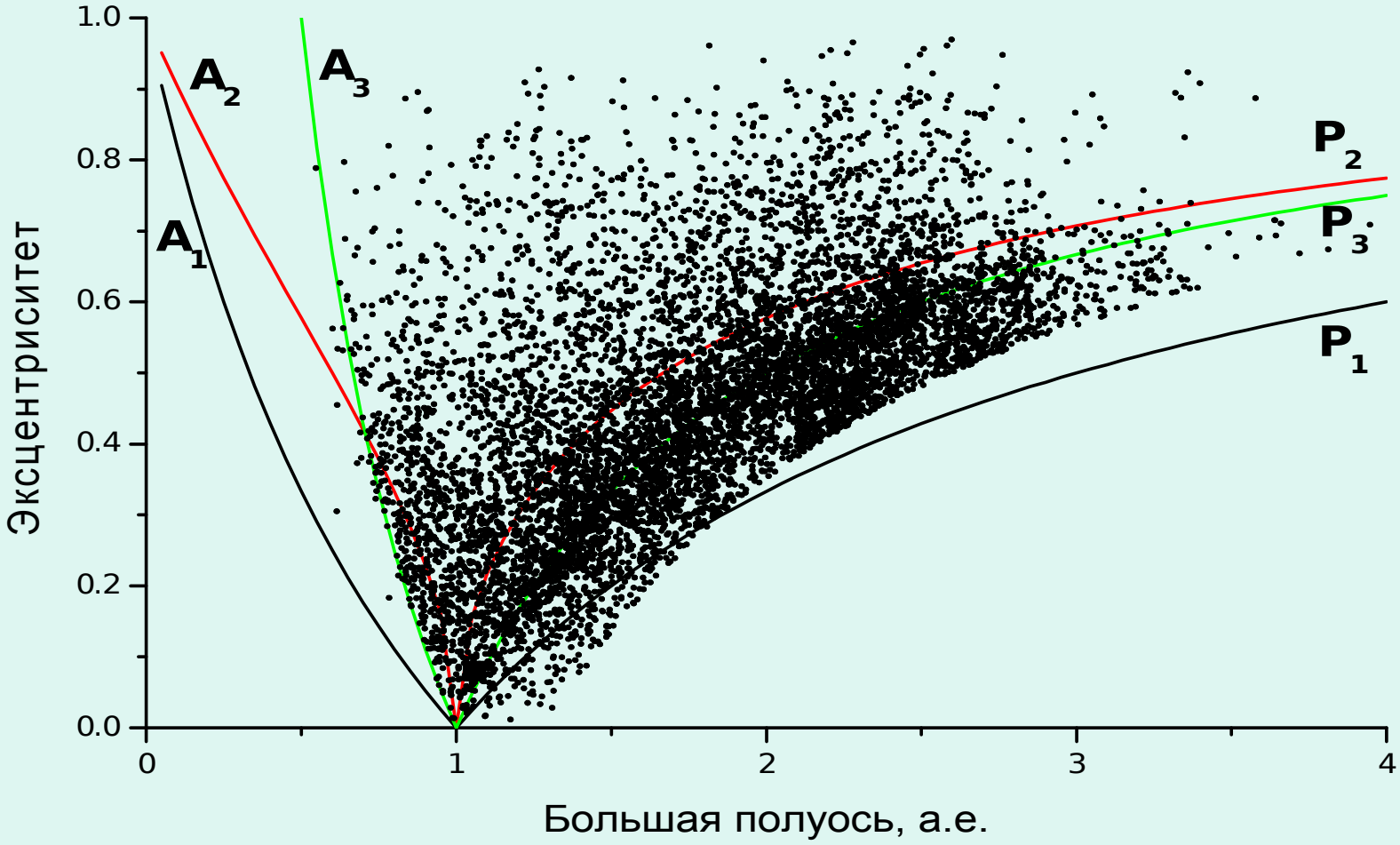
Распределение околоземных объектов



Распределение околоземных объектов в области ω