STELLAR INTRUDER IN AN EXOPLANETARY SYSTEM

Kálmán Posztobányi
Department of Astronomy
Loránd Eötvös University
Pázmány Péter sétány 1/A
H-1117 Budapest, Hungary
K.Posztobanyi@astro.elte.hu

Abstract To investigate the effect of a star approaching a planet-star system I made calculations for the orbital elements of the planet and initial conditions of the intruder star.

As a result of these calculations I got 2D and 3D graphicons about the changes of parameters at close encounters between stars.

Keywords: Stellar – Close Encounters – Exoplanets

1. Introduction

Examination is made of the effect of a star approaching a planet-star system. When a passing star encounters a planetary motion, it causes the changing of the semimajor axis a, the eccentricity e, and the inclination i of the planet's orbit. Calculations were made for penetrating encounters, when the approach of the intruder was less than a, and for close encounters, when the closest approach of the intruder was 1-10 a.

First let's consider the examined parameters and some of the results. Lyttleton and Yabushita [1] calculated the variation of the orbital elements. A Gaussian distribution of star velocities was assumed in order to estimate the cumulative effects of series of encounters. They used the central-limit theorem of probability and supposed that the velocity of the passing perturbing star was $v = 20$ km/s, the star density 0.1 star/pc^3, and the examined time was $T = 4 \cdot 10^9$ years.

If stars are passing at a distance of some ten times greater than a, the cumulative effects are found to be of the order of 10^{-4} for Δe and Δi, and 10^{-6} for $\frac{\Delta}{a}$. For close stellar encounters direct numerical integrations show that both capture and disruption (expulsion of the planet) can occur.

Yabushita [2] examined the stellar perturbations of orbits of comets with long-periods and extremely eccentric orbits when the shortest distance between the passing star and the Sun is greater, than the aphelion distance of the comet. It was found that although the energy perturbation is only a few percent of the bounding energy of the comet, changes in r_p (perihelion distance) of a few AU can occur. Close encounters were investigated by numerical integration using random initial conditions. The probability of the expulsion of comets depends on the closest approach p and is 0.031 for $p = 10^2$ AU, 0.006 for $p = 10^3$ AU, and 0.001 for $p = 10^4$ AU.

Hills [3] reported the results of computer simulations of close encounters between a planet-star system and a stellar intruder. Using a Shampine-Gordon (variable order, variable stepsize) integrator the inputs were the closest approach p and the velocity v of the intruder. When p was $2 - 3a$, the result was orbit-increasing or dissociating of the planetary system. For $p > 3a$ mild shrinking occured. Close encounters are disruptive, in many cases disruption can occur. Another case is the planet capturing, when the stellar intruder captures the planet.

The effect of the mass and the impact velocity of the intruder was studied by Hills and Dissly [4]. In their simulations the mass of the intruder was 0.1 - 100 times the mass of the star of the star-planet system. They examined the cross sections for dissociation, the changing of the orbital energy and the eccentricity of the planet. According to their results if the impact velocity is less, than the orbital velocity, the planet's orbit shrinks, otherwise it expands. The star-planet system is soft if the bounding energy of the system is less than the kinetic energy of the intruder. Contrary to a myth that hard binaries shrink, soft binaries expand in encounters with stellar intruders, one should speak of fast or slow intruder limit (between the expanding and the shrinking) rather than soft or hard binary limit. This behaviour was first noticed by Aarseth and Hills [5], but they simulated star-star systems, not star-planet systems. Their study was based on computations relative to binary stars in which the binary and the intruder had nearly the same masses that is all three masses were equal. They examined the influence of encounters of the major planets with random massive objects.

Distant encounters and their importance on the dynamical evolution of planetary systems was studied by Brunini [6]. He considered the two-body problem with a massive primary and with smaller secondary in circular orbit. The system was perturbed by a third massive body. Closest approaches and high velocity encounters were examined too. In the case of penetrating encounters the closest approach is less, than the separation of the system. The change of the internal energy can be described accurately by an impulse approximation. In this case the time of relevant interaction is shorter than the orbital period of the system. Distant encounters take place in a time span longer than the orbital period. The relative position of the binary members changes considerably. The interaction cannot be described by impulse approximation. The interaction can be studied by means of the Fokker-Planck equations or direct numerical integration. Brunini [6] made an application to the outer planets of the Solar System. Distant encounters may excite the orbital velocity of the planets. The secular transfer of impulse increases the orbital eccentricity, if e is negligible before the encounter. If the orbit is eccentric, the above eccentricity increaments adds to e quadratically, as in a random walk. It was made some approximations: the eccentricity of the planets was constant, perturbations from other planets were considered negligible. The regions of chaotic motion were very small. Brunini [6] obtained surprisingly high Δe values, which was 0.003 for Neptune, with the closest star-star approach $p = 230$ AU. The observed eccentricity for Neptune is 0.0085.

An application to the Kuiper belt was made too by Brunini [6]. In this case an algorithm was used to determine the effect of successive perturbations on binary systems by distant passing intruders. The algorithm is valid for eccentric orbits. Random passing stars almost completely thermalise the belt beyond some thousands AU from the Sun. The flattened structure of the Kuipert belt cannot extend much farther than this distance.

The frequencies of stellar encounters in an enviroment depend on the number-density of stars and the relative velocities. Table 1 shows the frequencies of encounters in some enviroments.

Table 1. Encounter frequencies. The large encounter-frequency at the Galactic Centre is due to the large velocities of stars.

enviroment	**stellar density**	**encounter frequency**
Solar environment	$0.1\ \mathrm{star/pc^3}$	$1\ \frac{\mathrm{encounter}}{\mathrm{star \cdot Gyr}}$
Stellar cluster	$1.5\ \mathrm{star/pc^3}$	$20\ \frac{\mathrm{encounter}}{\mathrm{star \cdot Gyr}}$
Galactic Centre	$100\ \mathrm{star/pc^3}$	$100\ \frac{\mathrm{encounter}}{\mathrm{star \cdot Gyr}}$

2. Application of the model to intruders

The Lie integration is a fast integration method for the differential equations of motion of celestial bodies, applying Lie-series. The basic idea to use the implicit Lie transformation to integrate the n-body problem is due to Gröbner [8], Hanslmeier and Dvorak [6] simplified the calculation of the Lie-terms and derived a recurrence formula. They solved in an optimal way the 2-body problem, then they derived a similar method for the solution of the n-body problem.

This integration method has two major advantages. First, it is a relatively fast method, about 3 - 10 times faster than the n-body problem of high accuracy by

Schubart and Stumpff [9]. Second, because larger step lengths can be used (e.g. a step length of 135 days for Jupiter), roundoff errors are smaller.

The Solar System is not isolated in space. Random passing stars, molecular clouds, and our galaxy, the Milky Way can play a role in the dynamical evolution of the planetary system and the cometary cloud. The dynamical effect of random passing stars is not negligible for the major planets. The effect of the passing stars could had been stronger, when the Solar System was young, especially if the Sun and the planets had come into existence in a stellar cluster. If it happened so, we do not know how much time the Solar System had spent in its parent cluster, how many closeup stellar approaches had formed its dynamics. I investigate the effect of close encounters taking place between a passing star and Sun or a star in an exoplanetary system.

I examined a special three-body problem, in which a stellar intruder is acting on a star-planet system. I was interested in whether the orbit of the planet shrinks or increases. My goal was to calculate the changing of the orbital elements (semimajor axis, eccentricity, inclination) of the planet and the changing of the bounding energy during the approach of the intruder to the system.

For the calculations I selected a special star-planet system, in which the mass of the star is 1 Sun-mass, and the mass of the planet is 1 Earth-mass. The initial orbit of the planet is circular, the semimajor axis a of the orbit is 1 AU, so the circular velocity v of the planet is $30km/s$. The basic plane of reference for the calculations is the planet's orbital plane.

The mass of the stellar intruder is 1 Sun-mass too, the relative velocity u between the two stars is $30km/s$. In the initial position the passing star is at $R_{init} = 1720$ AU from the star of the star-planet system. In a spherical coordinate system two angle are necessary for the position, λ and β. The angle λ is measured along the orbit of the planet, its value is between 0 and $360\circ$. The direction of $\lambda = 0\circ$ is opposite sense to the direction of the initial velocity of the planet. The angle β is between the intruder star and the plane of the planetary orbit, with values between -90 and $90°$. The initial velocity vector of the passing star is parallel to the star-star section, and its initial distance from this section is p. If gravity did not work and the intruder star conserved the direction of the initial velocity, then the minimal distance between the two stars would be p. The value of p is between 5 and 20 AU in the computations.

With these initial conditions I obtained the following results.

2.1 Bounding energy

The bounding energy of a celestial body is its mechanical energy, which is the sum of the kinetic and potential energy. Fig. 1 shows the change of the bounding energy in time.

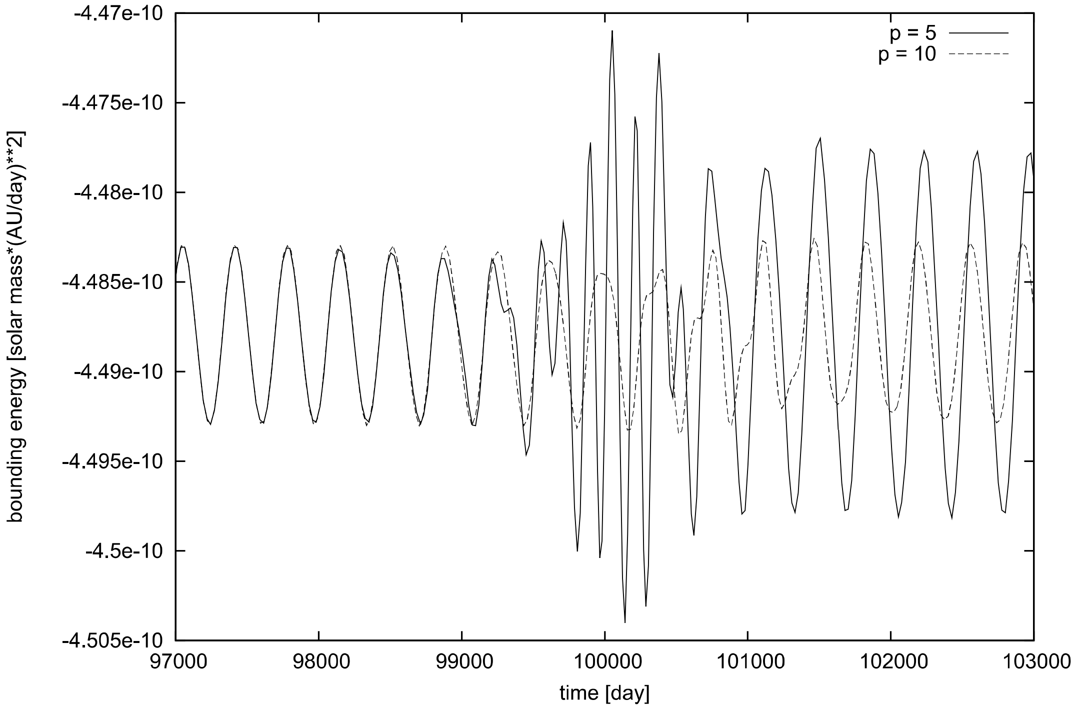

Figure 1. changing of bounding energy in time

The approach occurs about the 100 000th day. The value of the bounding energy oscillates before and after the approaching. The bounding energy of the planet is not proportional to the semimajor axis of its orbit because the potential energy of the intruder star is significant during the approach. The period of the change of the semimajor axis period of the planet before and after the approaching is the period of the planet-circulation, 360 days, but at the approaching it is 180 days.

2.2 Orbital elements

I investigated, how do the size, form and tilt of the orbital plane of the planet change, so the examined orbital elements are the semimajor axis a, the eccentricity e and the inclination i of the planet.

2.3 Changing of a in time

The changing of the semimajor axis becomes significant when the approaching intruder star is at 100 AU from the star-planet system. To show the effect of the distance on the changing of the semimajor axis I made calculations for $p = 5$ and 10 AU. In case of these values of p the effect of the gravitation of the intruder star is strong enough, but the star-planet system does not perish. In Fig. 2 we can see the result, the rising and then the declining of the amplitude

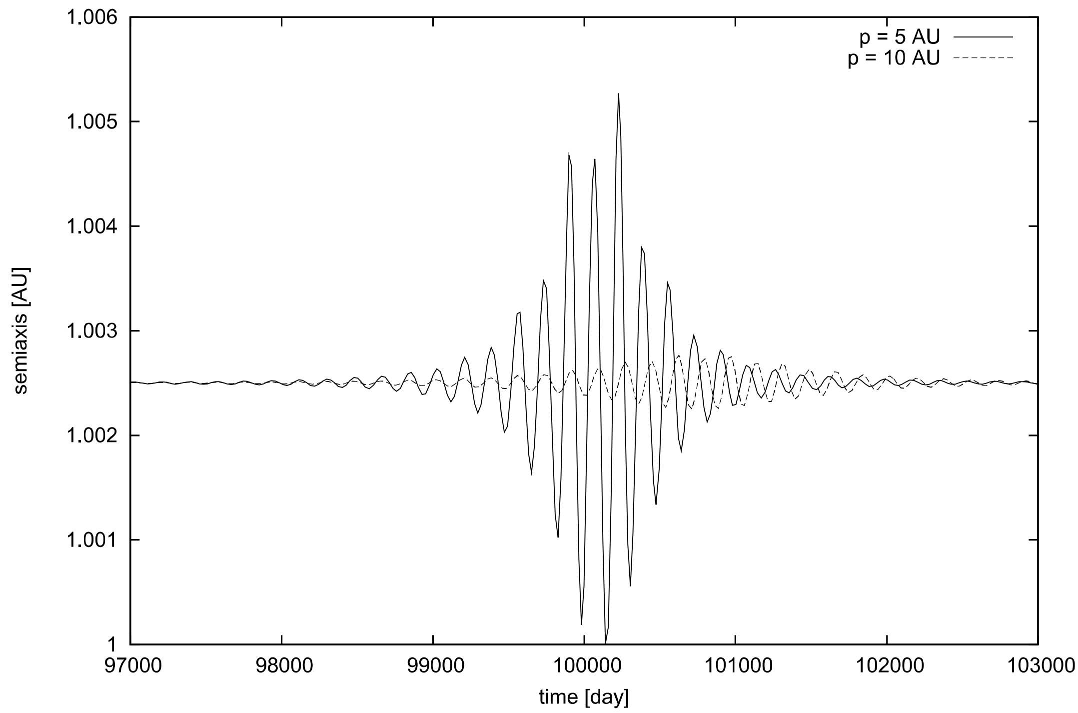

Figure 2. changing of a in time

of the semimajor axis-undulation; after relatively grand oscillations the new value of the semimajor axis is almost the initial; the difference between the initial and the final semimajor axis is low. The maximal amplitude of the oscillations of the semimajor axis is a hundred times greater, than the initial-final difference. When the value of p was 10 AU, the maximum of the undulation of the semimajor axis occured later than at $p = 5$ AU. The cause of this is the later pericentrum passage on the $p = 10$ AU orbit. The curves show that the period of the change of the semimajor axis is close to the half-period of the planet-circulation.

2.4 Changing of e in time

The value of the eccentricity of the orbit undulates and usually becomes greater during the passing, particularly at low initial values of p (see Fig. 3). The period of the change of the eccentricity is close to the half-period of the planet. The amplitude of the undulation is greater, than the difference between the initial and the final value of the eccentricity. When $p = 10$ AU, the maximal amplitude of the oscillations of the eccentricity is thirty times greater, when $p = 5$ AU, two times greater, than the initial-final difference. When the amplitude of the undulation is the biggest, the distance between the maxima following each other is about the half-period of the planet.

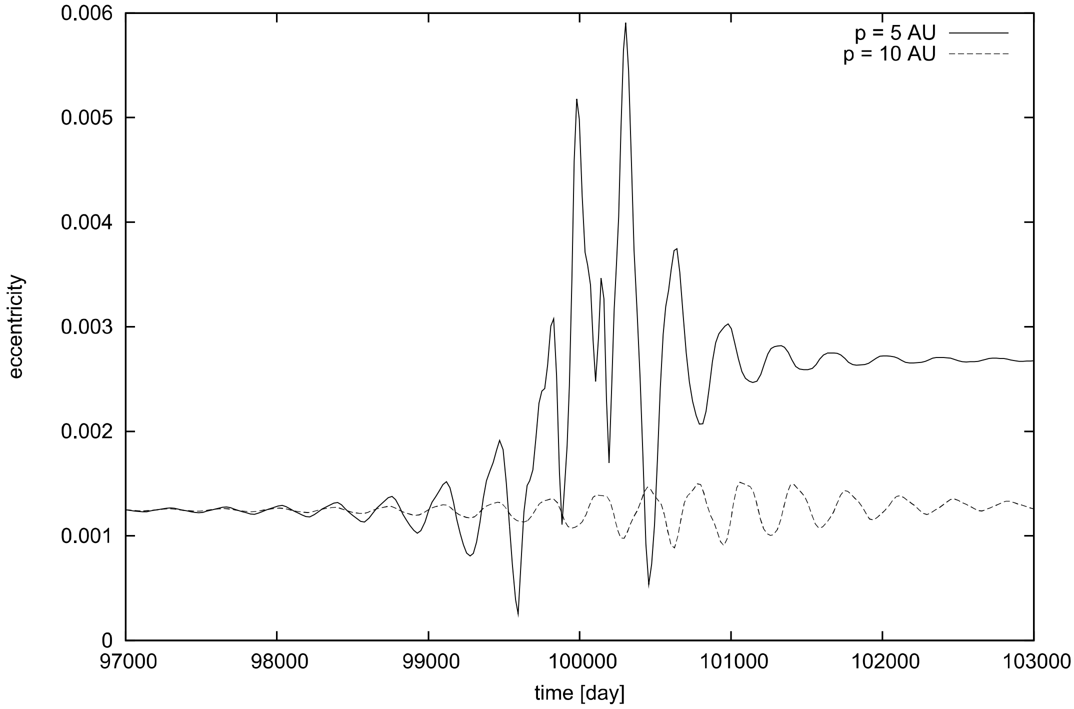

Figure 3. changing of e in time

2.5 Changing of i in time

For the computation of the changing of a and e I used the planar three-body problem, but for Fig. 4 the motion of the three bodies is not planar, the angle between the initial velocity of the intruder star and the orbital plane of the planet is $2.8°$. When $p = 10$ AU, the maximal amplitude of the oscillations of the inclination is forty times greater, when $p = 5$ AU, three times greater, than the difference between the initial and the final inclination (see Fig. 4). The approaching in both cases reduced the inclination of the orbital plane. The period of the change of the inclination is close to the half-period of the planet-circulation.

2.6 Changing of a, e, i in λ

In Fig. 5, Fig. 6 and Fig. 7 the differences between the initial and final values of the orbital elements a, e and i are shown for different values of λ, where λ is the initial longitude of the planet along its orbit. The initial inclination of the orbital plane is $2.8°$. When $p = 4$ AU, the semi-major axis vs. λ function has two maxima at $\lambda = 105°$ and at $\lambda = 295°$, the maxima of the eccentricity vs. λ function are at at $\lambda = 110°$ and at $\lambda = 300°$, and the maxima of the inclination vs. λ function are at at $\lambda = 55°$ and at $\lambda = 275°$. For bigger values

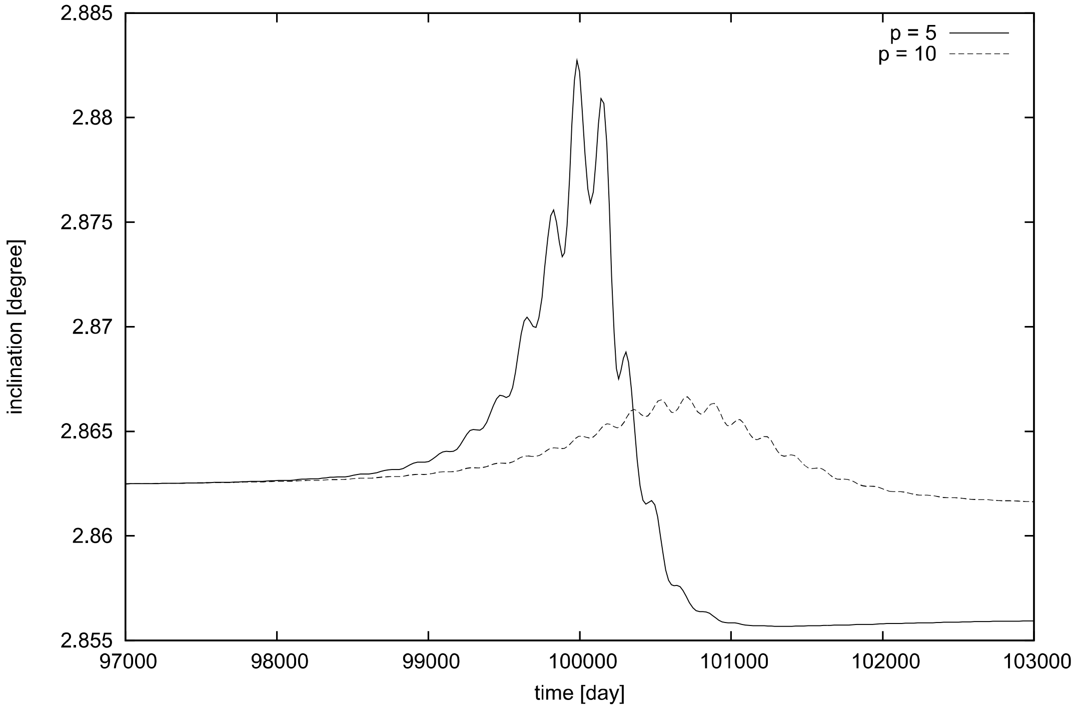

Figure 4. changing of i in time

of p the maxima of a, e, i are shifted to the right. When a grows, e and i grow as well.

2.7 Changing of a, e, i in β

β is the angle of arrival of the intruder star with respect to the orbital plane of the planet. The initial inclination of the orbital plane is $0.0°$. The difference between the initial and final value of the semimajor axis of the planet is biggest, when $\beta = 0$ (see Fig. 8). The orbit in all cases decreases. The final eccentricity is biggest, when $\beta = 0$ too. The change of the inclination is 0, when $\beta = 0°$, and maximal, when $\beta = 35°$ (see Fig. 9 and Fig. 10). The curves are symmetrical with respect to the initial conditions.

2.8 Changing of a, e, i as the function of $p = z_0$

Let the parameter p equal to the z_0-component of the initial position of the intruder star. In Fig. 11, Fig. 12 and Fig. 13 we can see the difference between the initial and the final values of the orbital elements in the case of different values of z_0 and y_0. When z_0 is smaller than 2.5, a decreases, the orbit shrinks, its eccentricity significantly grows. When $y_0 = 3$, the difference between the initial and the final inclinations can be $4.5°$. The cause of the asymmetry of the curve in Fig. 13 is the non-zero initial inclination of the orbit of planet.

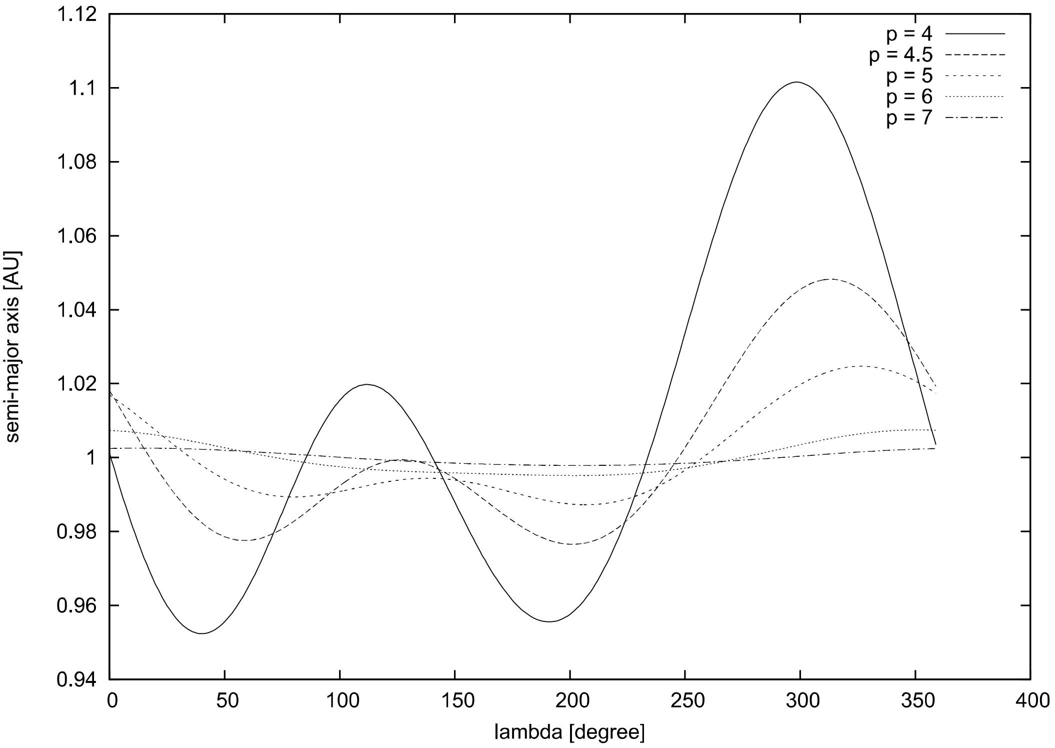

Figure 5. changing of a in λ

2.9 Changing of the orbital elements at close encounters

Fig. 14, Fig. 15 and Fig. 16 show the changing of a, e and i at close encounters, when the intruder star arrives perpendicular to the orbital plane of the planet. The parameters x and y mean the shift of the initial velocity vector of the intruder star. Their unit is AU. If both x and y are zero, the initial velocity vector points to the parent star. For other x, y values the initial velocity vector is parallel to the parent star-intruder star line and the coordinates of the intruder star is x and y on the plane which is perpendicular to the line. The change of a, e, i is indicated as the function of x and y. Fig. 14 shows, that the difference between the initial and the final semimajor axis is great, when the approach between the intruder star and the planet is close. Negative semimajor axis means, that the final value of the semimajor axis is also negative, and the planet is not bound. The initial value of the eccentricity is 0. According to Fig. 15 the new value of the eccentricity can be very big - especially if the planet is free. Fig. 16 shows, that the inclination can have any value.

2.10 Stellar intruder at star-two planets system

What is the effect of another planet? I tried to show it. I calculated the change of the orbital elements of the planet in the presence of an additional

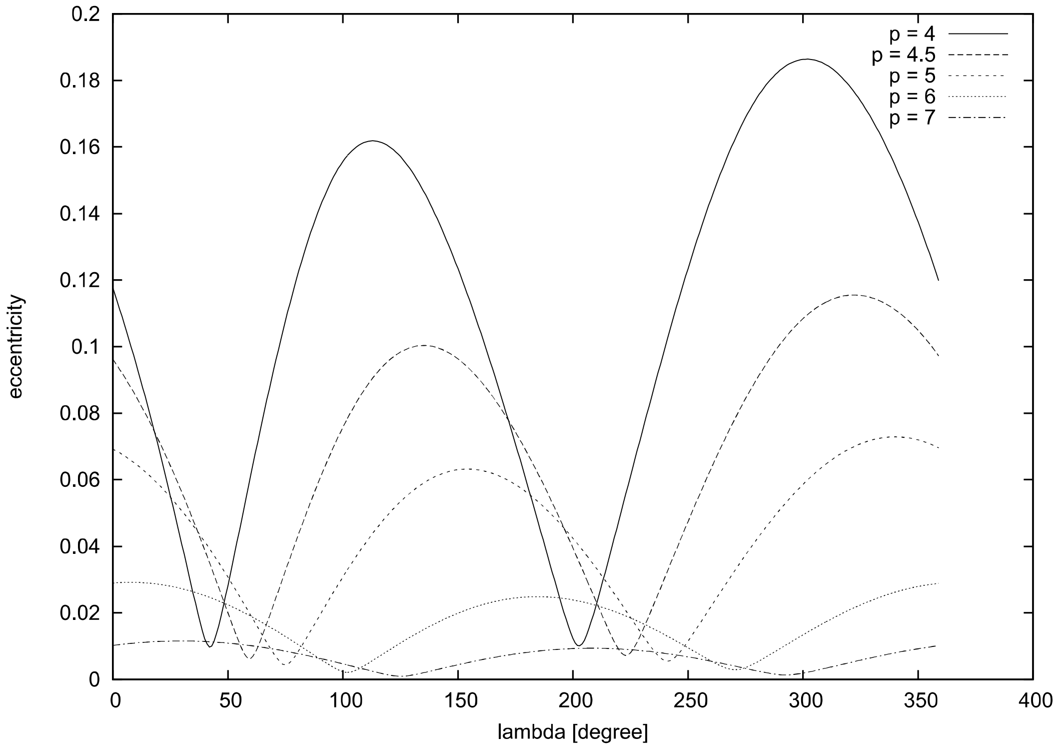

Figure 6. changing of e in λ

planet which has one Jupiter-mass and the semimajor axis of its orbit is 5 AU. Let us sign it with J, the planet of Earth-mass with E, and the home star with S. In Table 2 the number 45.3 in the column of $S - E$ means, that the final bounding energy is 45.3 per cent of the initial one, so the orbit expanded. In Table 2 we can see, that the expansion of the orbit is greater in $S - E$ system than in $S - E - J$ system. It should to investigate if this is true establishment in the case of different masses end semi-majos axes of the second planet J.

Table 2 shows the probability of shrinking of the orbit of the inner planet in a star-planet ($S - E$) and in a star-two planets ($S - E - J$) system. We can see that in the presence of a new, Jupiter-mass planet in the model, the probability of the shrinking of the orbit of the inner planet is bigger.

3. Conclusions

I considered encounters between star-planet systems and an intruder star and determined the effect of the distance- and angle parameters of the passing star. The examined encounters were close. The change of the semi-major axis and the inclination of the orbit of planet is significant, when the stellar approach is close - 4-5 a -, but they quickly fade, when the minimal distance between the two stars is greater.

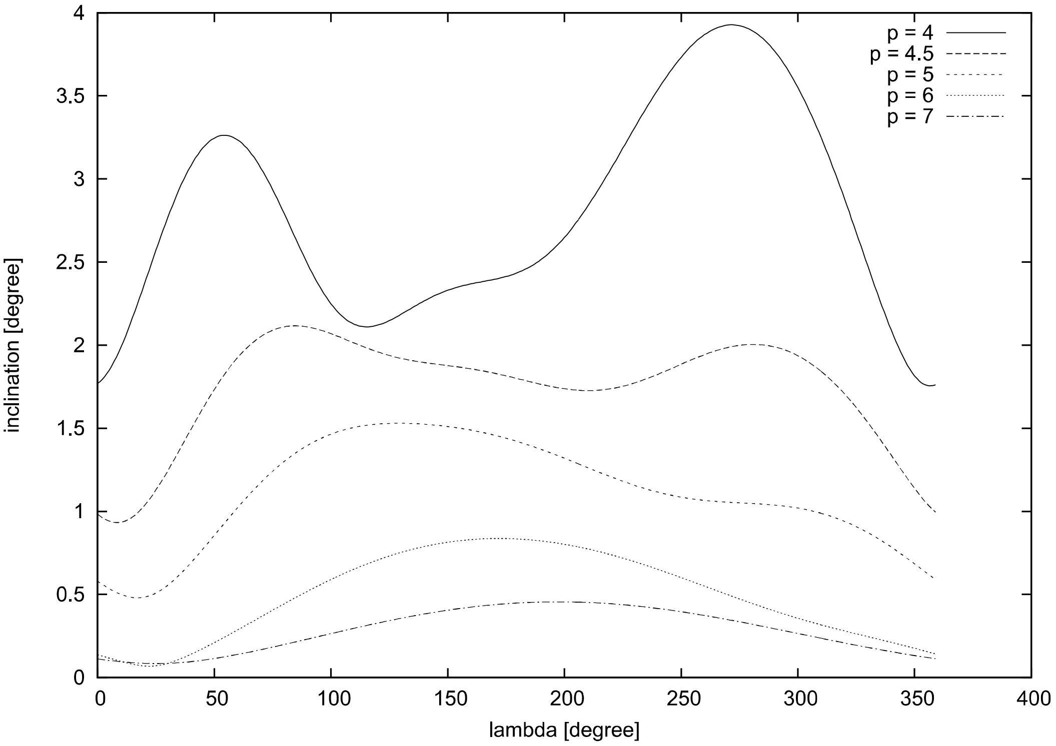

Figure 7. changing of i in λ

Table 2. The relative changing of the bounding energy in the presence and absence of a second planet. $S - E$ means a Sun-Earth, $S - E - J$ means a Sun-Earth-Jupiter system. The Earth-mass first planet has 1 AU semimajor axis orbit, the orbit of the Jupiter-mass second planet 5 AU semimajor axis. The probability of the shrinking of the orbit of the inner planet is expressed by per cent for different values of λ and β.

λ	β	$S - E$	$S - E - J$
0.0	0.0	45.3	99.1
45.0	0.0	43.8	100.0
90.0	0.0	32.2	99.3
180.0	0.0	43.3	100.0
270.0	0.0	33.9	99.2
0.0	45.0	41.3	97.5
0.0	90.0	9.1	98.3

Is there any pragmatic significance of the investigation of such close approaches? Neither in our Solar System, nor in any exoplanetary system there was any observation of close stellar encounter yet. Are they frequent events at all? We know that when two galaxies merge in one another, impacts of stars do not occur. Close encounters between stars are still extraordinary. In the environment of the Sun only one closer than 100 AU encounter is to be expected within 10^{12} years. However, close approaches are more frequent in dense core

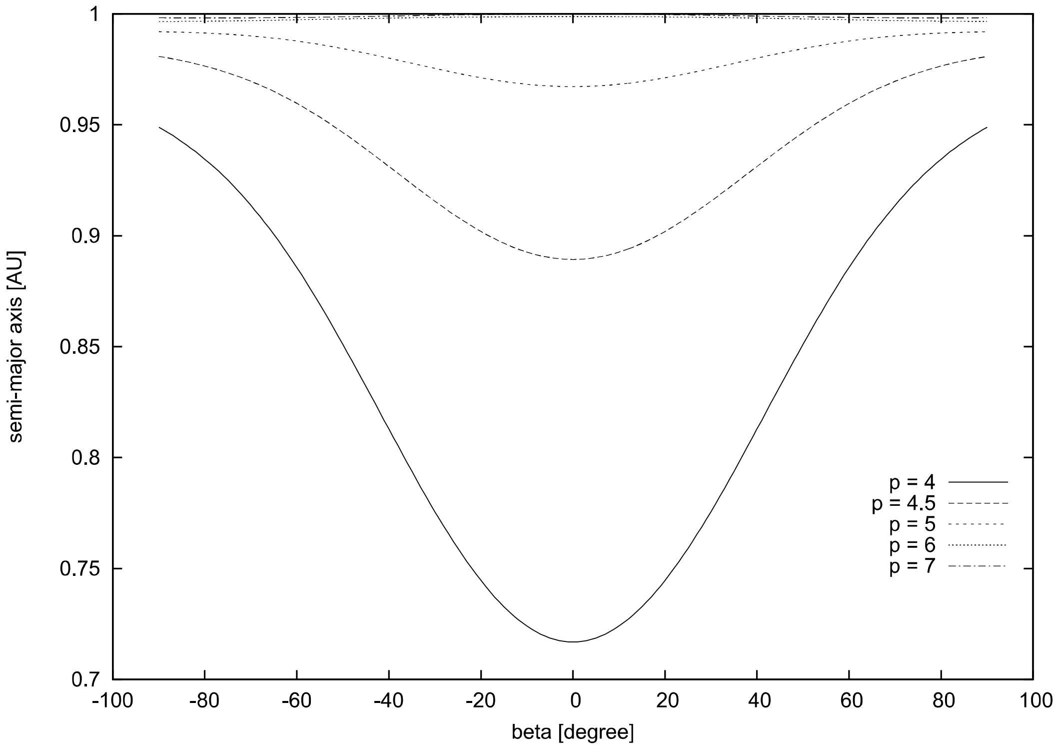

Figure 8. changing of a in β

star-clusters. If the Solar System were born in a stellar cluster, it could have several close approaches, these encounters could affect the dynamics of the planetary system. Tracks of such stellar encounters, their effects on the dynamical evolution may be observable in the Solar System and exoplanetary systems, if they could be separated from the effect of the planets.

Acknowledgments

The support of the Austrian-Hungarian Scientific and Technology Cooperation, grant number A-12/04 is acknowledged.

References

[1] Lyttleton, R. A., Yabushita, S.: 1965, "The Effect of Stellar Encounters on Planetary Motions", *Monthly Notices of the Royal Astronomy Society* **129**, pp.105-125

[2] Yabushita, S.: 1972, "Stellar Perturbations of Orbits of Long-Period Comets", *Astronomy and Astrophysics* **16**, pp. 395-340

[3] Hills, J. G.: 1984, "Close Encounters between a Star-planet System and a Stellar Intruder", *The Astronomical Journal* **89**, pp.1559-1564

[4] Hills, J. G., Dissly, R. W.: 1989, "Close Encounters between Star-planet Systems and a Stellar Intruders. II. Effect of the Mass and Impact Velocity of the Intruder", *The Astronomical Journal* **98**, pp.1069-1082

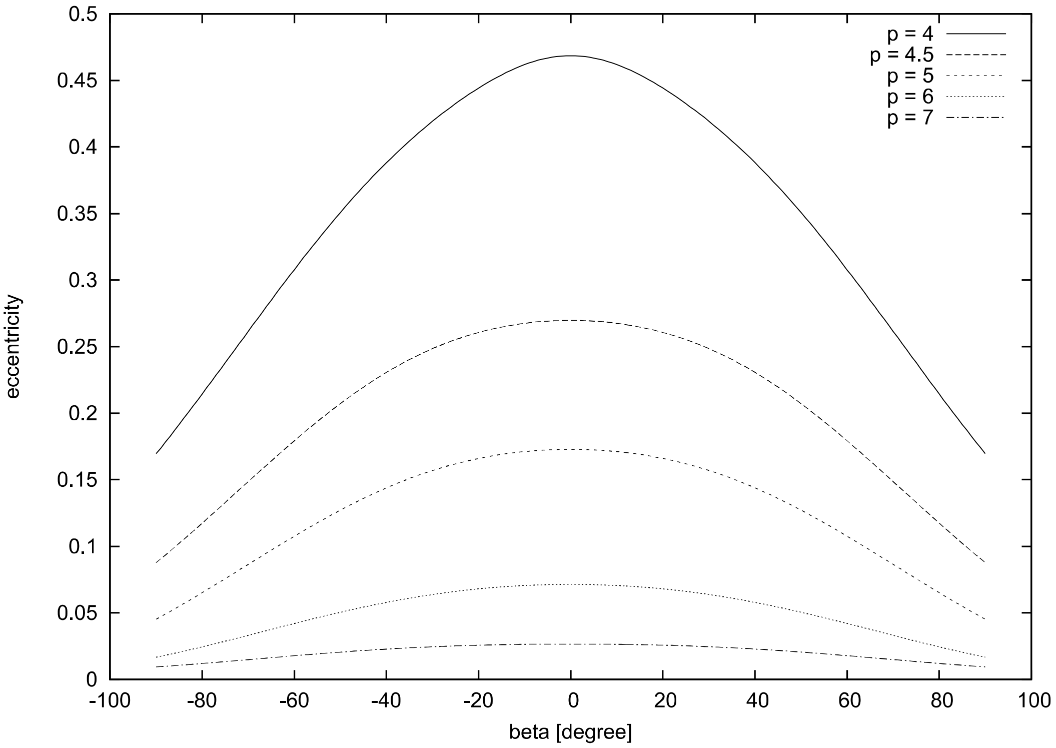

Figure 9. changing of e in β

[5] Aarseth, S. J.; Hills, J. G.: 1972, "Close Encounters between Star-planet Systems and a Stellar Intruders.", *Astronomy and Astrophysics* **21**, pp. 255

[6] Brunini, A.: 1995, "The Effect of distant Stellar Encounters on Planetary Systems. II", *Astronomy and Astrophysics* **293**, pp.935-940

[7] Hanslmeier, A.; Dvorak, R.: 1984, "Numerical Integration with Lie Series", *Astronomy and Astrophysics* **293**, pp.935-940

[8] Gröbner, W.: 1967, "Die Lie-Reihen und ihre Anwendungen" *VEB Deutscher Verlag der Wissenschaften, Berlin*

[9] Schubart, J.; Stumpff, P.: 1966, "On an N-Body Program of High Accuracy for the Computation of Ephemerides of Minor Planets and Comets" *Veröffentlichungen des Astronomischen Rechen-Instituts Heidelberg* **18**, pp.31

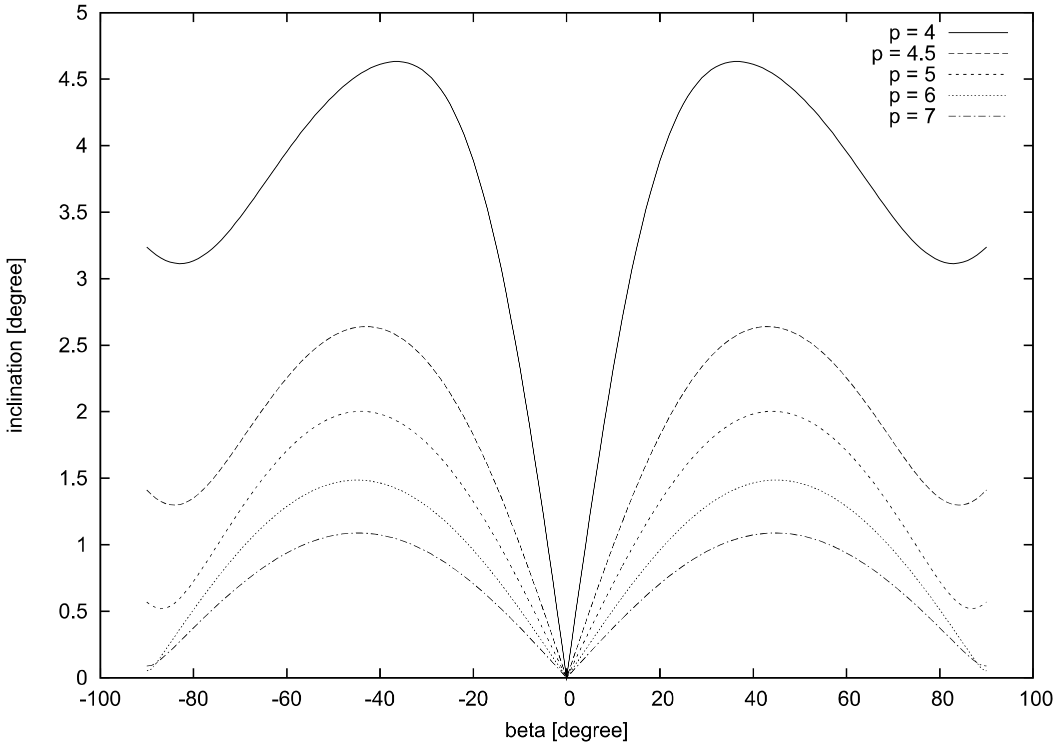

Figure 10. changing of i in β

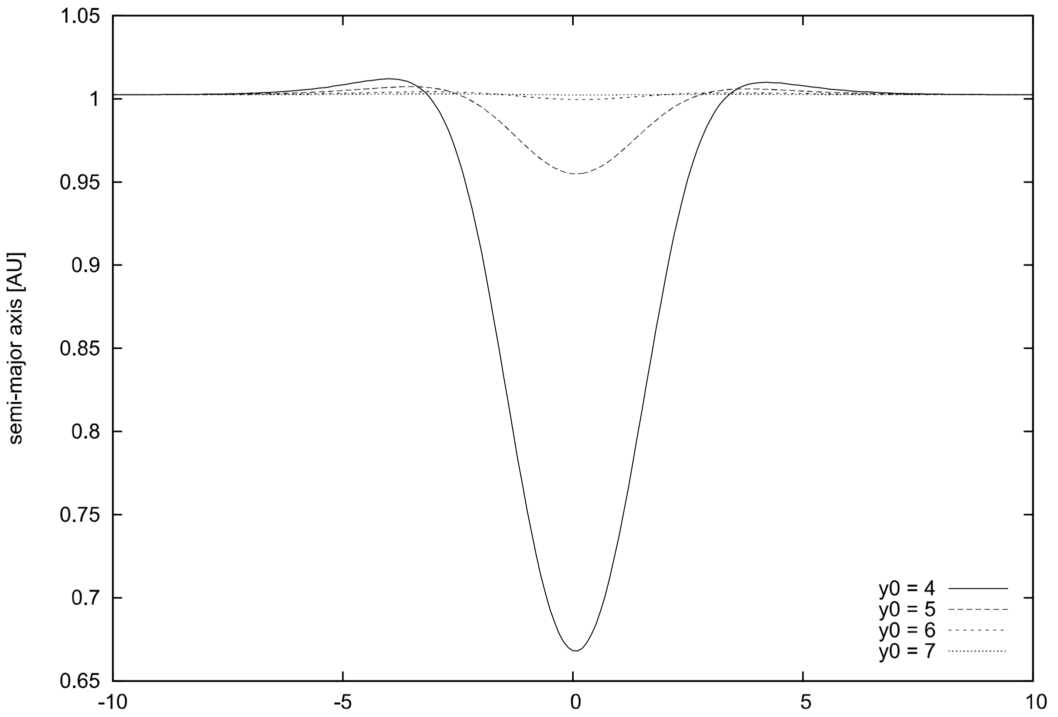

Figure 11. changing of a in parameter z_0

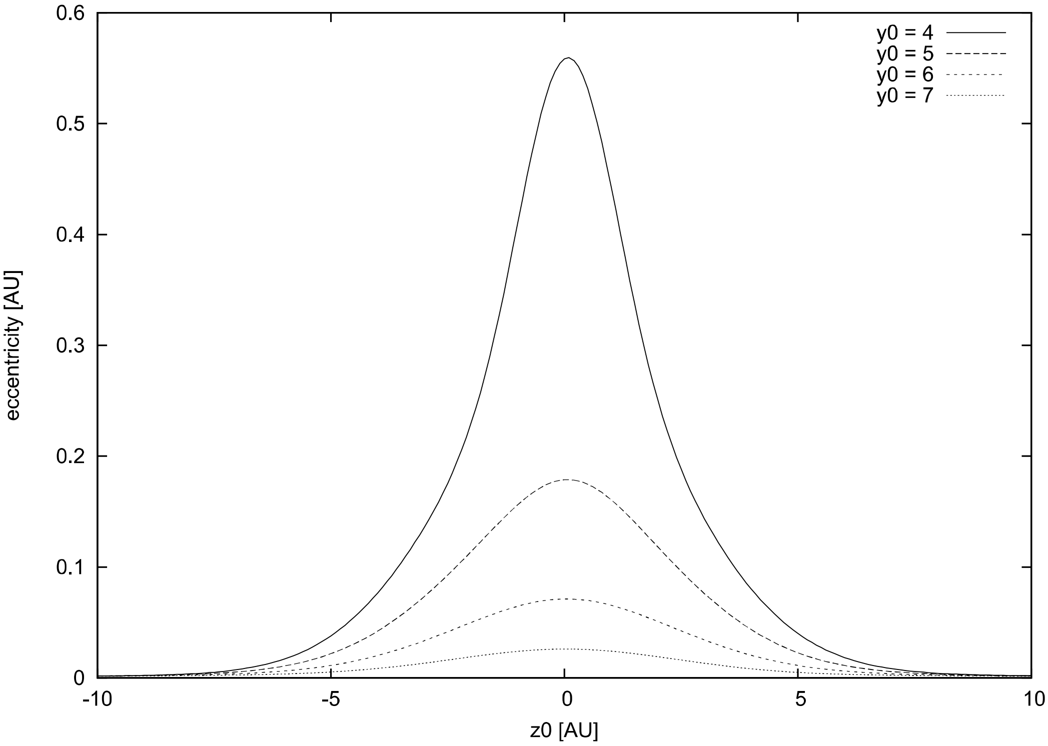

Figure 12. changing of e in parameter z_0

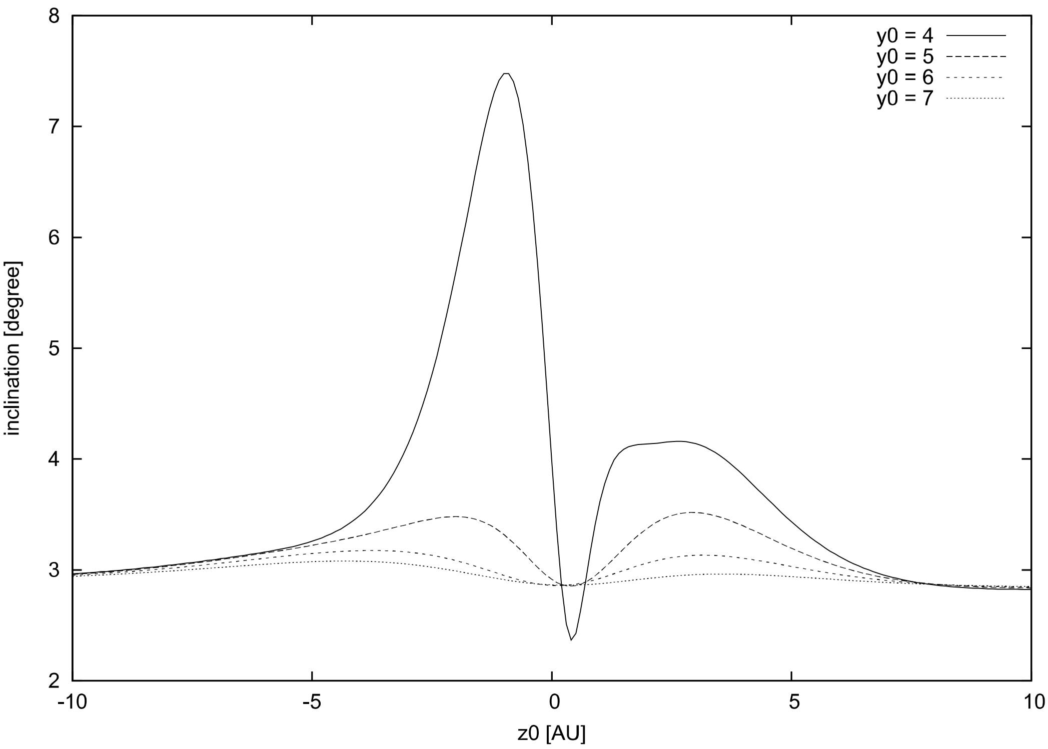

Figure 13. changing of i in parameter z_0

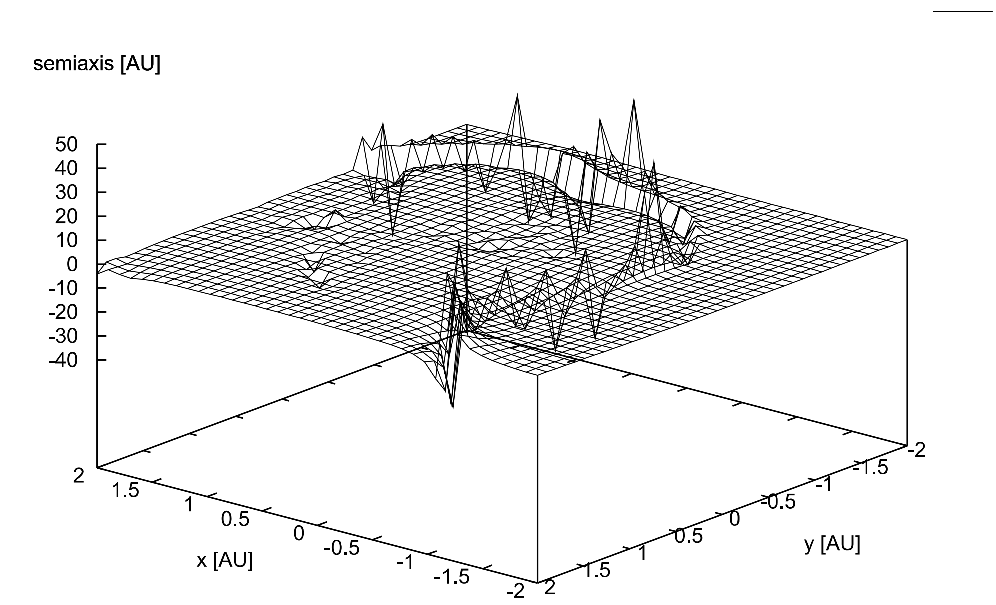

Figure 14. changing of a at close encounters

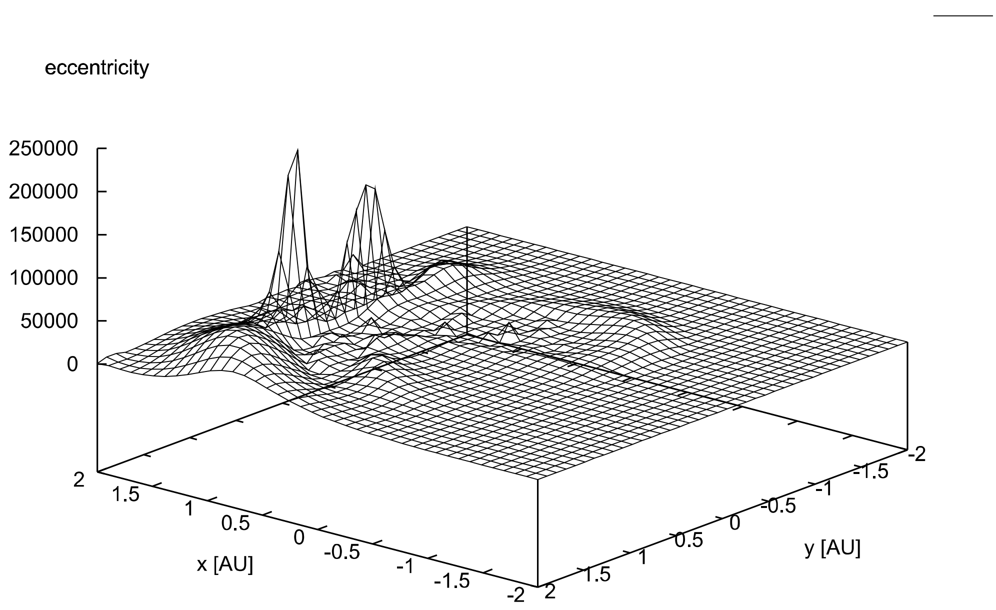

Figure 15. changing of e at close encounters

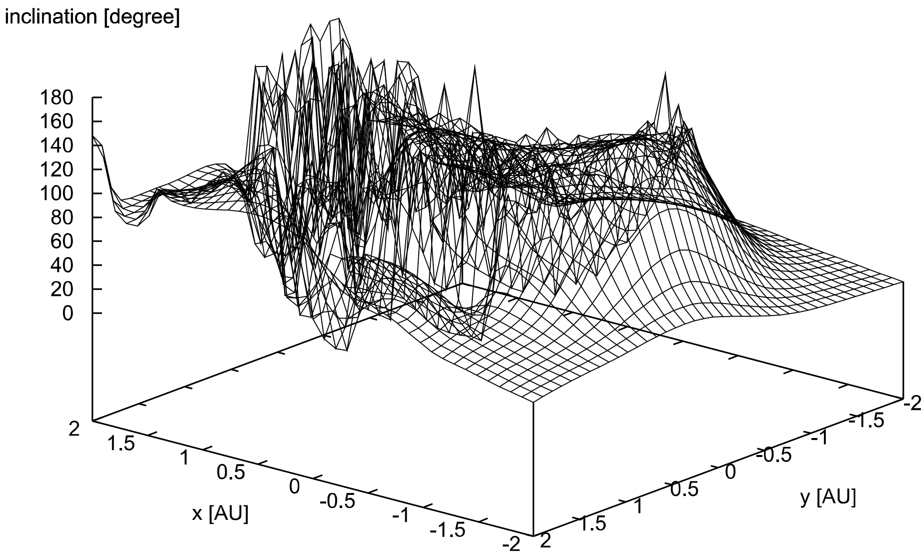

Figure 16. changing of i at close encounters