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THE POSSIBLE BELTS FOR EXTRASOLAR PLANETARY SYSTEMS

Ing-Guey Jiang,[1] M. Duncan,[2] and D. N. C. Lin[3]

RESUMEN

Desde la década de los 90 se han descubierto más de 100 planetas extrasolares. A diferencia del Sistema S
estos planetas tienen excentricidades en un amplio intervalo, desde 0 hasta 0.7. El primer objeto del Cintu
de Kuiper se descubrió en 1992. Se plantea la cuestión de si los sistemas planetarios extrasolares podrían t
estructuras como el Cinturón de Kuiper o el de los asteroides. Investigamos la estabilidad de estos sistemas
distintas excentricidades con los métodos de Rabl & Dvorak (1988) y Holman & Wiegert (1999). Sostene
que la mayor parte de los sistemas planetarios extrasolares pueden tener cinturones en las regiones externas
obstante, encontramos que las órbitas de gran excentricidad son muy efectivas para destruir estas estructu

ABSTRACT

More than 100 extrasolar planets have been discovered since the 1990s. Unlike those of the solar system, t
planets' orbital eccentricities cover a huge range from 0 to 0.7. Incidentally, the first Kuiper belt object
discovered in 1992. Thus an interesting and important question will be whether extrasolar planetary syst
could have structures like the Kuiper belt or asteroid belt. We investigate the stability of these plane
systems with different orbital eccentricities by similar procedures to Rabl & Dvorak (1988) and Holma
Wiegert (1999). We claim that most extrasolar planetary systems can have their own belts at the o
regions. However, we find that orbits with high eccentricity are very powerful in depletion of these populati

Key Words: **STARS: PLANETARY SYSTEMS**

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1. INTRODUCTION

In recent years, the number of discovered extrasolar planets is increasing quickly due to astronomers' observational effort and therefore interest in dynamical study in this field has been renewed.

These discovered planets, with masses from 0.16 to 17 Jupiter masses (M_J), have semimajor axes from 0.04 AU to 4.5 AU and also a wide range of eccentricities. Moreover, there is a mass-period correlation for discovered extra-solar planets, which gives a paucity of massive close-in planets. Jiang, Ip & Yeh (2003) claimed that although tidal interaction could explain this paucity (Pätzold & Rauer 2002), the mass-period correlation might be weaker at the time when these planets were just formed. Gu, Lin & Bodenheimer (2003) and Sasselov (2003) also have done very interesting work on close-in planets. Therefore, some of these extrasolar planets' dynamical properties are very different from the planets in the solar system.

Nevertheless, similarities between extrasolar and solar planets do exist. For example, there is a new discovery about a Jupiter-like orbit very recently, i.e. (semimajor axis $a = 3.65$ AU) was detected.

On the other hand, some planetary systems
claimed to have discs of dust and they are rega
as young analogues of the Kuiper belt. For ex
ple, Greaves et al. (1998) found a dust ring arc
a nearby star ϵ Eri and Jayawardhana et al. (2
detected the dust in the 55 Cancri planetary sys
Particularly, the β Pictoris planetary system h
warped disc and the influence of a planet might
plain this warp (Augereau et al. 2001).

Given the fact that many extrasolar planets
bital eccentricities are very big and some of them
could have analogues of the Kuiper belt, it woul
interesting to investigate in what environments
conditions the belts could exist for a planetary
tem. Following Rabl & Dvorak (1988) and Hol
& Wiegert (1999), we use the critical semimajor
as a tool to explore the unstable zone where it w
be difficult for a belt to exist for a given plane
system.

We will explain the basic model in Section 2
Section 3, we study the cases of one planet.

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2. THE MODEL

A direct force integration of the equation of motion is required for the computation of the orbital evolution of our systems. We adopt a numerical scheme with Hermite block-step integration which has been developed by Sverre Aarseth (Markino & Aarseth 1992, Aarseth, Lin & Palmer 1993).

We consider a range of ratio ($\mu = M_p/(M_p+M_*)$) of masses (M_p and M_*), where M_p is the planetary mass and M_* is the mass of the central star. We also consider a range of orbital eccentricity (e_p). The semimajor axis of the (inner) planet is set to be unity for systems with one (two) planet(s) such that all other lengths are scaled with its physical value. We adopt $G(M_* + M_p) = 1$ so that the planetary orbital period is 2π.

We mainly determine the inner and outer critical semimajor axis, i.e. the innermost and outermost semimajor axes at which the test particles at both $\theta = 0°, 90°$ survive. The definition of survival here is that the distance between the test particle and the central star must be smaller than a critical value R_d during a time T_d. The value of R_d is arbitrarily set to be 3 times the planetary initial semimajor axis and we choose $T_d = 2\pi \times 10^4$. Therefore, more precisely, the inner critical semimajor axis is: within the region between the planet and central star, the outermost semimajor axis that a test particle can survive for T_d, and the outer critical semimajor axis is: out of the region between the planet and central star, the innermost semimajor axis that a test particle can survive for T_d.

Based on several test runs, we find that the value of a_c does not change significantly if T_d is increased to $2\pi \times 10^6$. That is, planets which can survive for $2\pi \times 10^4$ can usually remain attached for a much longer timescale. Thus, we find the critical semimajor axis a_c to be a useful parameter to classify our results (Dvorak et al. 2004).

3. THE SYSTEMS OF ONE PLANET

We determine both the inner and outer critical semimajor axes for a system with one planet moving around the central star. The area between inner and outer critical semimajor axes can be regarded as an "unstable zone". We get the width of the unstable zone by subtracting the value of the inner critical semimajor axis from the value of the outer one.

We determine these critical semimajor axes for

TABLE 1A
Critical Semimajor Axis When $\mu = 0.005$

	inner	outer
$e = 0.0$	0.7	1.5
$e = 0.2$	0.5	1.9
$e = 0.4$	0.3	2.1
$e = 0.6$	0.2	2.2
$e = 0.8$	0.1	2.5

TABLE 1B
Critical Semimajor Axis When $\mu = 0.001$

	inner	outer
$e = 0.0$	0.8	1.3
$e = 0.2$	0.6	1.6
$e = 0.4$	0.4	1.8
$e = 0.6$	0.2	2.1
$e = 0.8$	0.1	2.2

TABLE 1C
Critical Semimajor Axis When $\mu = 0.0001$

	inner	outer
$e = 0.0$	none	none
$e = 0.2$	0.7	1.3
$e = 0.4$	0.5	1.6
$e = 0.6$	0.3	1.8
$e = 0.8$	0.1	1.9

If the mass of the central star is assumed t
1 $M_\odot$, the planet has about 5 M_J for the resul
Table 1a and has about 1 M_J for the results in T
1b. From Tables 1a and 1b, we find that the re
are quite similar for these two cases. Approxima
the inner critical semimajor axis is about 3/4
the outer critical semimajor axis is about 3/2 w
the eccentricity $e = 0$. After we increase the
centricity, the inner critical semimajor axis bec
about $(1 - e)3/4$ and the outer critical semim
axis becomes about $(1 + e)3/2$. This is reason
because the pericentre is at $(1-e)a$ and the apo
tre is at $(1+e)a$ where a is the semimajor axis o
planet and thus the planet's orbit covers a large
dial range, the critical semimajor axis should ch
correspondingly.

However, from the results in Table 1c, when
mass of the planet is much less (one order less)
M_J, the planet depletes nothing and thus both
inner and outer critical semimajor axes do not
in the case of zero eccentricity. Interestingly, w

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4. THE SYSTEMS OF TWO PLANETS

Interestingly, there are two belts of small bodies in the solar system and these two are located in very different environments: the asteroid belt is between two planets and the Kuiper belt is located at the outer part of the planetary disc. Therefore, it will be important to study multiple planetary systems and determine the physical locations where we can possibly have stable belts.

To simplify the model and as a first step, we choose the case of two planets, both with mass about M_J, i.e. $\mu = 0.001$. The inner planet will be planet 1 and the outer planet will be planet 2 hereafter. The stability of this system depends on their separation and also orbital eccentricities. To reduce the parameters, we always set the initial eccentricity of planet 2 to be zero but study the effect of different initial eccentricity of planet 1 only.

These two planets are in fact interacting with each other. When the initial eccentricity of planet 1 is small, the interaction is weaker and planet 2 stays moving on a nearly circular orbit. When the initial eccentricity of planet 1 is bigger, the interaction becomes much stronger and the eccentricity of planet 2 gradually increases in our simulations.

We checked the critical semimajor axis of planet 2 for different eccentricities of planet 1 and we found that when planet 1 is initially located at $r = 1$, planet 2 should be at about $r = 3$ to make the system stable during 10^4 orbital periods of planet 1.

Therefore, we set the semimajor axis of planet 1 to be unity, the semimajor axis of planet 2 to be 3 and both at $\theta = 0^\circ$ initially. We then begin to place test particles to determine the inner and outer critical semimajor axes for both planets. Tables 2a-b are the results.

When the eccentricity is 0 or 0.2, we found that there could be an asteroid belt-like population between these two planets. The system is quite stable and thus the results in last section, i.e. Table 1b, gives us good hints for the size of the unstable zone around planet 1 though the unstable zone does expand a bit for this system with two planets. However, when the eccentricity is larger, there is no stable zone between these two planets and the most possible location to have a belt is outside outer critical semimajor axis of planet 2. This result tells us that if the eccentricities of the planets in the solar system were not between 0 and 0.2, but much larger, it is unlikely that there would be an asteroid belt

TABLE 2A
Critical Semimajor Axis of Planet 1

	inner	outer
$e = 0.0$	0.7	1.3
$e = 0.2$	0.6	1.7
$e = 0.4$	0.3	none
$e = 0.6$	0.2	none
$e = 0.8$	0.1	none

TABLE 2B
Critical Semimajor Axis of Planet 2

	inner	outer
$e = 0.0$	2.3	3.9
$e = 0.2$	2.3	3.9
$e = 0.4$	none	3.9
$e = 0.6$	none	3.9
$e = 0.8$	none	7.5

example, 16 Cyg B, 55 ρ^1 Cnc, τ Boo.

It will be interesting to see the effect of a ondary companion star on the planetary syste which a planet moves around the binary prim Thus, assuming an equal mass binary, we deter the critical semimajor axis of the binary secon for the cases that the eccentricity of the binary 0.2 and 0.6. We assume the planet has mass a 1 M_J, the initial eccentricity ranges from 0 to with respect to the binary primary. Both the bi secondary and the planet begin from $\theta = 0^\circ$. Ta 3a-b are our results. Most of the discovered pla are stable since their binary separations are n bigger than the critical semimajor axes.

On the other hand, the binary might affect extension of possible belt populations. To inv gate this point further, we now use two test part (at $\theta = 0^\circ$ and 90°) to determine the critical s major axis of the binary. We find that the cri semimajor axis of the system becomes bigger in der to make the test particles survive. For the of $e_\mathrm{b} = 0.2$, the critical semimajor axis a_b is a 20. For $e_\mathrm{b} = 0.6$, a_b is about 36. This result not depend on the details of other parameters as the initial eccentricity of the planet or the s major axis of the test particles. Because the cri semimajor axis becomes much bigger, the pres of a binary secondary might affect the extensio even existence of possible Kuiper belt populatio

6. CONCLUSIONS AND IMPLICATIONS

Table 3a
Critical Semimajor Axis When $e_b = 0.2$

	a_b
$e = 0.0$	4.1
$e = 0.2$	4.5
$e = 0.4$	4.9
$e = 0.6$	5.2
$e = 0.8$	5.4

Table 3b
Critical Semimajor Axis When $e_b = 0.6$

	a_b
$e = 0.0$	9.7
$e = 0.2$	10.1
$e = 0.4$	10.6
$e = 0.6$	11.1
$e = 0.8$	11.5

sults should be applicable to discovered extrasolar planetary systems. In addition to those systems with one planet, systems with two planets are studied and the effect of a companion star is also investigated.

We find that highly eccentric orbits are very powerful in depletion of belt-like populations such as the asteroid belt and the companion star might restrict the extension of such populations.

On the other hand, as emphasized by Yeh & Jiang (2001), the planet should dynamically couple with the belt over the evolutionary history. That is, the planet's mass and orbital properties would determine the existence and affect the position of the belt, but if the belt is massive enough, it will in turn influence the planet, too. This is particularly important during the early stage of planetary formation since the circumstellar belt is more massive then. For example, Jiang & Ip (2001) noted that interaction with the belt could bring the planetary system of υ And to its current orbital configuration.

Moreover, according to Jiang & Yeh (2004), the probability that the planet moves stably around the outer edge is much smaller than near the inner edge. This conclusion is consistent with the principal result in Jiang & Yeh (2003).

What could we learn for the solar system from their theoretical result? From the observational picture of the asteroid belt, we know that: (a) the outer edge looks more diffuse and (b) Mars is moving stably close to the inner edge of the asteroid belt but Jupiter is quite far from the outer edge. One possible explanation is that Jupiter is much more massive and thus those planetesimals close to Jupiter w have been scattered away during the formation o solar system. If we apply the model of Jiang & (2004) to the asteroid belt and the point mass w represents the planet in their model can also re sent larger asteroids, their theoretical result prov another choice to explain both (a) and (b).

It is known that there is another belt in the lar system, the Kuiper belt, after the first ob was detected (Jewitt & Luu 1993). Allen, Berns & Malhotra (2001) did a survey and found that could not find any Kuiper belt objects (KBOs) la than 160 km in diameter beyond 50 AU in the o solar system. If we apply the model of Jiang & (2004) to this problem and the point mass w represents the planet in their model now repres larger KBOs moving within the Kuiper belt, we that their theoretical results provide a natural m anism to do this orbit rearrangement: larger K might have been moving towards the inner edg the belt due to the influence from the belt.

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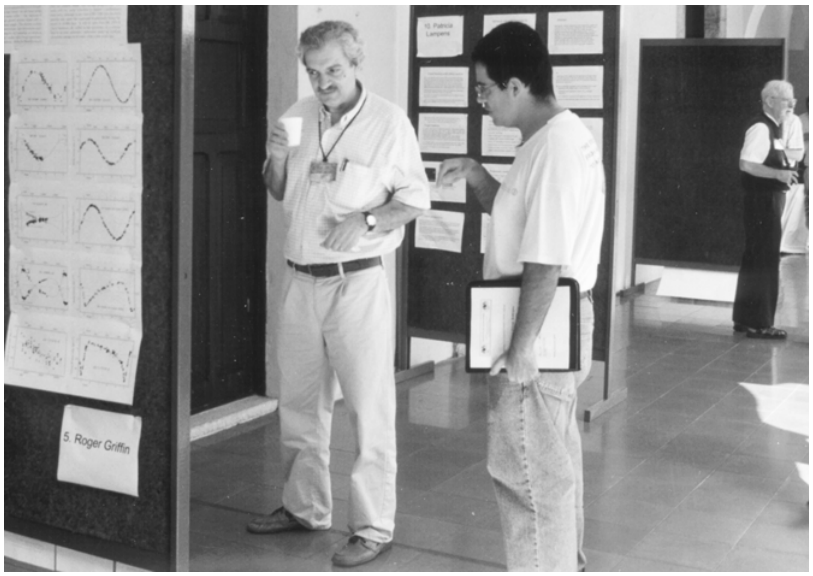
DISCUSSION

Scarfe – What units are your belt masses expressed in?

Jiang – In units of a solar mass.

Sterzik – In order to confirm putative belts around extra-solar planet systems, what wavelength reg would you recommend? In other words, what radii and temperatures do you expect to have stable config tions?

Jiang – Because the current results have been detected in the far infrared, this is probably the right ch



Guillem Anglada and Abraham Luna.