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The planetary system of upsilon Andromedae

Ing-Guey Jiang[1] and Wing-Huen Ip[2]

[1] Academia Sinica, Institute of Astronomy and Astrophysics, Taiwan
[2] Institute of Astronomy & Institute of Space Science, National Central University, Taiwan

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Abstract. The bright F8 V solar-type star upsilon Andromedae has recently been reported to have a system of three planets of Jovian masses. In order to investigate the orbital stability and mutual gravitational interactions among these extrasolar planets, both forward and backward integrations from the latest observed orbital elements for all three planets' orbits have been performed under the coplanar assumption. We reconfirm that the middle and the outer planet have strong interaction leading to large time variations in the eccentricities of these planets, which was shown by the previous studies. However, we discuss the validity of the ignorance of the innermost planet. We argue that this planetary system is likely to be stable and oscillate around current orbital elements since it was formed. We suggest that one possible way to produce these orbital elements: the innermost planet has very low eccentricity but the outermost planet has high eccentricity could be the interaction with the protostellar disc.

Key words. celestial mechanics – stellar dynamics – planetary systems

1. Introduction

As a result of recent observational efforts, the number of known extrasolar planets increased dramatically. Among these newly discovered planetary systems, upsilon Andromedae system appears to be the most interesting one because of the presence of three planetary members (Butler et al. 1999).

Since the discovery of the planetary system of upsilon Andromedae, the dynamics of this multiple planetary system with intriguing orbital configuration has drawn a lot of attention. Table 1 is the latest (as of 21st August, 2000) orbital elements obtained by the Marcy's group (`http://exoplanets.org/esp/upsandb/upsandb.html`). It would be interesting to understand the origin of the orbital configurations of these three extrasolar planets and their mutual interactions.

Table 1. The orbital elements

Planet	$M \sin i/M_{\rm J}$	a/AU	e	ω (deg)
B	0.69	0.059	0.01	316.4
C	2.06	0.827	0.23	247.2
D	4.10	2.56	0.35	250.6

It is a remarkable fact that the eccentricities of the companion planets increase from 0.01 for the innermost member to a value as large as 0.35 for the outermost member. An interesting question is therefore if orbital evolution leads to this configuration. This question is related to whether these planets interacted strongly in the past.

Without studying the past history, several groups have investigated this system by forward orbital integration from the observed orbital elements. Laughlin & Adams (1999) simplified the model computation by ignoring the innermost planet. They found that the upsilon Andromedae system should experience chaotic evolution for all parameters derived from present observations. In spite of the large amplitudes of the eccentricities of the middle and outer planets, this system could remain non-crossing over a time interval of 2–3 Gyr for a significant number of the cases studies.

Rivera & Lissauer (2000) did many extensive calculations for both nearly coplanar systems and mutually inclined orbits. For coplanar systems, they found that the nominal Lick data systems are more stable than the system with the nominal Advanced Fiber Optic Echelle (AFOE) parameters. They also explore different values of the overall mass factor $m_{\rm f} = (\sin i)^{-1}$ and found that the systems with smaller $m_{\rm f}$ are more stable for both Lick data systems and AFOE data systems.

Rivera & Lissauer (2000) also ignored the innermost planet for some calculations and they found that two-planet systems with AFOE parameters typically last much longer than their three-planet analogs.

Send offprint requests to: Ing-Guey Jiang,
e-mail: `jiang@asiaa.sinica.edu.tw`

In this paper, we focus on the most stable configuration in Rivera & Lissauer (2000), i.e. the coplanar Lick data system with $m_{\rm f} = 1$. First of all, we study the orbital interaction between three planets by a forward integration of 10^5 yrs. We analyze the interaction by comparing the numerical result to the analytical equations. The main goal of this analysis is to understand the validity of ignoring the innermost planet.

In order to study the past history and origin of the orbital elements, we perform the backward integration, which was not done in the previous work. In order to test the correctness of our calculations, we also do forward integration and check if the results are consistent with the results of Rivera & Lissauer (2000). We therefore do both forward and backward integrations of three-planet system for 10^6 yrs. We also do both forward and backward integrations of two-planet system for 10^9 yrs.

From these calculations, we found that it is a good approximation to ignore the innermost planet of the coplanar Lick data system with $m_{\rm f} = 1$ for a long term integration. This was already shown in Rivera & Lissauer's results of coplanar Lick data systems. (Their three-planet system survived at least 10^8 yrs and two-planet system survived at least 10^9 yrs.) What is new here is that we show that the results of backward integration behave similarly to the forward integration and therefore the system is likely to oscillate around current orbital elements since its formation. The origin of these orbital elements is complicated but we use one simple calculation of disc-planet interaction to argue that the protostellar disc might be important in causing these orbital elements.

In Sect. 2, we describe the simulation model. We analyze the planet-planet interaction for a time scale of 10^5 yrs in Sect. 3. In Sect. 4, we investigate the dynamical origin of the orbital elements. We provide the conclusions in Sect. 5.

2. The simulation models

2.1. The orbital integration

We use mixed variable symplectic (MVS) integrator in the SWIFT package (Levison & Duncan 1994) to integrate the orbit for the planetary system of upsilon Andromedae. The initial condition was from Table 1, which is the latest orbital elements determined by Marcy's group. We modified MVS integrator to be able to do backward integration. This can be done because of the integrator's symplectic property. We follow Rivera & Lissauer (2000) to use 0.23 days as our timestep for both forward and backward integration when all three planets are included. We also follow Rivera & Lissauer (2000) to use 2.42 days as our timestep for both forward and backward integration of two-planet system.

2.2. The planet-disc interaction

In the calculation of planet-disc interaction, we assume both the mass of the central star and the gravitational constant G to be unity. The masses of the planets are set to be zero, so there is no interaction between different planets.

We include a disc into the Hermit integrator developed by Sverre Aarseth (Markino & Aarseth 1992; Aarseth et al. 1993) The disc has density profile as:

$$\rho(r,t) = \begin{cases} 0 & r \leq \epsilon \\ c \;\; r^{-11/4} \exp(-t/\tau) & r > \epsilon. \end{cases} \quad (1)$$

We choose $\epsilon = 0.01$, $c = 0.001$ and $\tau = 30$ so that the mass of the disc would be about 0.1 and the disc would be depleted in a time scale of 30.

3. The planet-planet interactions

The numerical integration of the three-planet system is expensive because the period of the innermost planet is only 4.617 days. Therefore, the innermost planet is usually ignored when one wishes to study long-term stability.

In order to see if the omission of the innermost planet is a good approximation, we analyze the interaction between three planets by comparing the numerical result of 10^5 yrs to the analytic equations in this section.

The initial condition of the numerical integration was from Table 1. The time variations of the semi-major axises and eccentricities are given in Fig. 1. Rather significant variations in eccentricities are found which can be understood in terms of planet-planet interaction. As usually encountered in celestial mechanics, the semi-major axes remain nearly invariant while the eccentricities could follow rapid variations of large amplitudes as a consequence of angular momentum exchange.

We can understand the details of this interaction from the results in Fig. 1 with the help of Eq. (2.144) and Eq. (2.147) in Murry & Dermott (1999):

$$\dot{C}_i = \frac{\mu_i}{2a_i^2}\dot{a}_i, \quad (2)$$

where C_i is the energy, $\mu_i = G(M_\star + M_i)$, a_i is the semi-major axis. The index i can be m for the middle planet and o for the outer planet. Therefore, $M_{\rm m}$ is the mass of the middle planet and $M_\star$ is the mass of the central star.

$$\frac{{\rm d}e_i}{{\rm d}t} = \frac{e_i^2 - 1}{2e_i}[2\dot{h}_i/h_i + \dot{C}_i/C_i], \quad (3)$$

where e_i is the eccentricity and h_i is the angular momentum.

The main result from the numerical simulation is that the semi-major axis of the middle planet does not change much but the eccentricity change quickly between 0.125 and 0.225. This tells us that $\dot{C}_{\rm m}$ is small from Eq. (2). Thus, from Eq. (3), we know that all the quick eccentricity variation is due to the angular momentum variation.

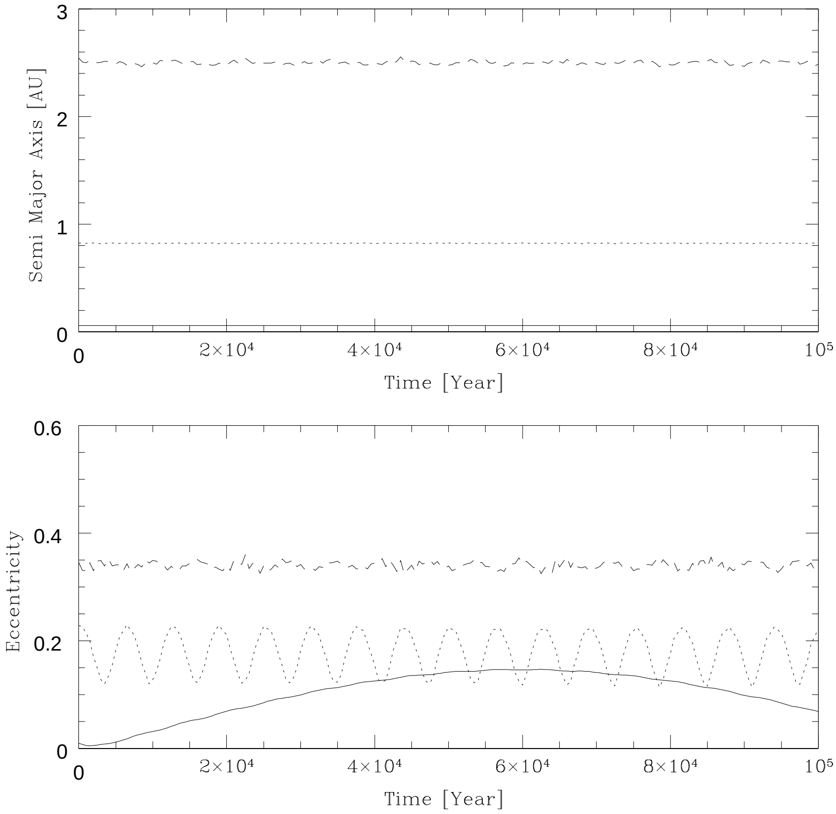

Fig. 1. The semi-major axes (top panel) and the eccentricities (bottom panel) of all planets as function of time, where the solid line is for the inner planet, the dotted line is for the middle planet and the dashed line is for the outer planet

Bottom panel of Fig. 1 showed that the frequencies of the eccentricity variations of the middle and outer planet are very close and thus the angular momentum change of the middle planet must be due to the forcing from the outer planet. The semi-major axis of the outer planet also has certain variation and this should be from the energy exchange with the middle planet because Eq. (2) tells us that the time derivative of semi-major axis is related to the time derivative of energy. The reason why the variation of semi-major axis of the middle planet looks so small is due to the form of Eq. (2): For the same $\dot{C}_i$, $\dot{a}_i$ is smaller for smaller a_i. The reason why the variation of e_i for the outer planet is smaller is partially because $(e_i^2 - 1)/(2e_i)$ for the outer is about -1.25 but -2.06 for the middle planet in Eq. (3). Therefore, the outer and middle planets are indeed interacting strongly.

On the other hand, from the bottom panel of Fig. 1, we see that the frequency of eccentricity variation of the innermost planet is very different from the other two planets and the semi-major axis is almost constant. The innermost planet does not involve that much of the dynamics of the middle and outer planets. Therefore, it is a good approximation to ignore the innermost planet when one needs to do it for a long-term integration.

4. The origin of orbital elements

The planetary system of upsilon Andromedae is interesting not only because of the presence of multiple planets but also because of the orbital configuration.

It is therefore important to investigate if orbital evolution leads to this current configuration: the innermost planet has very low eccentricity but the outermost planet has much higher eccentricity.

There are two obvious ways to lead to the current orbital elements of the exoplanets of upsilon Andromedae. One way is that even all of these three planets had similarly small eccentricities when they were form, the long-term orbital evolution can cause the outer two planets to have higher eccentricities. Another way is that, these orbital configuration was originally due to the disc-planet interaction when the system was formed. After that, the orbital elements are kept to be similar but oscillate around the current values.

We can investigate the first possibility by doing backward integrations. In order to check if our numerical code can produce the results which are consistent with the results of Rivera & Lissauer (2000), we also do the usual forward integrations.

Figure 2 are the results of both backward and forward integrations for 10^6 yrs. The semi-major axises of three planets are almost constant all the time except the small fluctuations for the outermost planet. However, the eccentricities of all three planets oscillate in very large amplitudes: the innermost planet oscillate between 0 and 0.15, the middle planet oscillate between 0.125 and 0.225, the outermost planet oscillate between 0.33 and 0.35. Therefore the orbital elements remain unchanged but just oscillate around the current observed values for both backward and forward integrations.

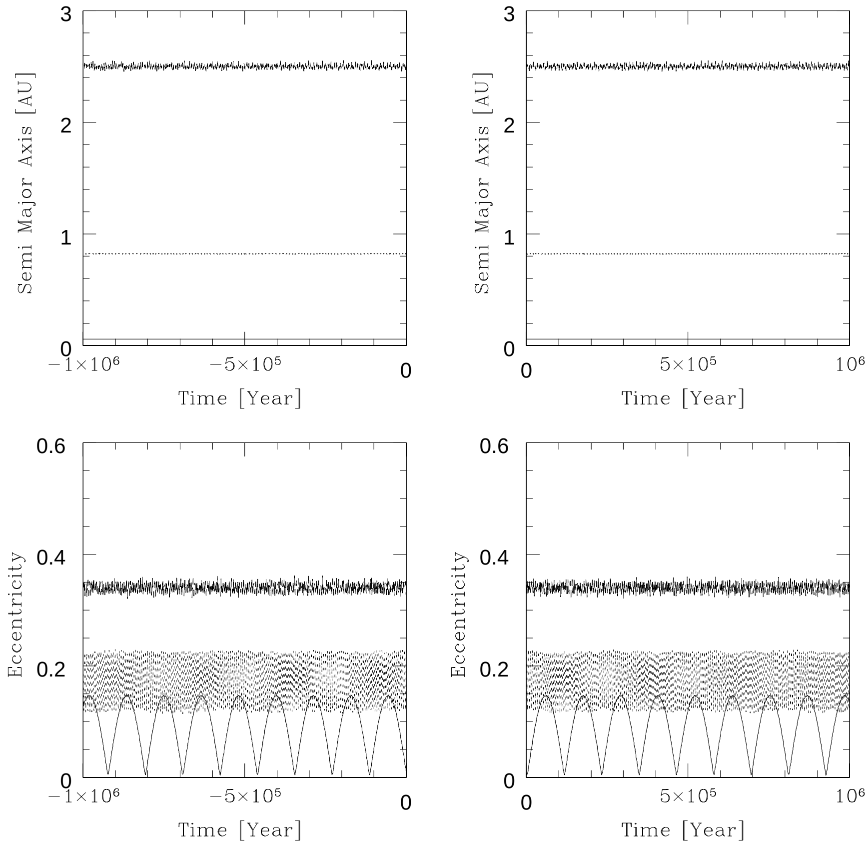

Fig. 2. The semi-major axes (top panels) and the eccentricities (bottom panels) of all planets as function of time for both backward (left panels) and forward (right panels) integrations, where the solid line is for the inner planet, the dotted line is for the middle planet and the dashed line is for the outer planet

To check if this is still the case for a longer time scale, we integrate 100 times longer, i.e. 10^8 yrs. We ignore the innermost planet in this case because the long-term integrations are far more expensive and from the last section we know that the ignorance of the innermost planet is a good approximation.

Figure 3 are the results of both backward and forward integrations for 10^8 yrs. The results are just the extension of the results in Fig. 2, so the orbital elements still oscillate around the current observed values for both backward and forward integrations of 10^8 yrs. From Fig. 3, we can see that it is already impossible to see the lines in the figure. We also integrate for a longer time scale (order of Gyr). The result remains to be the same and it is not necessary to provide this figure in the paper because it looks almost the same as Fig. 3.

From the above calculations of forward integrations, it is encouraging that we can produce the results which are consistent with those of Rivera & Lissauer (2000). From the calculations of backward integrations, we know that the long-term orbital evolution might not be able to produce the current orbital configuration because the orbital elements do not really change but just oscillate around the current values. Thus, we should test if the orbital configuration was originally due to the planet-disc interaction when the system was formed. After the formation process, the orbital elements keep to be similar but oscillate around the current values.

We use the model we described in Sect. 2.2 to simulate the planet-disc interaction. We assume the inner planet is at $r = 0.8$ and the outer planet is at $r = 2.5$ and both of them have eccentricity $e = 0.2$ initially. Figure 4 is the result for time evolution of both semi-major axis and the eccentricity.

Because of the interaction with the disc, both eccentricities increase and oscillate. The existence of the disc makes the gravitational force experienced by the planets more complicated and increase the eccentricities. (If there were energy dissipation during the planet-disc interaction, the eccentricities of both planets should decrease.) However, the outer planet's eccentricity is pumped to a higher value. During the depletion of the disc, the eccentricities of both planets gradually settle down to a stable value and stop oscillation. The final eccentricity of the outer planet is higher than the final eccentricity of the inner planet. Further, the final semi-major axes of both planets are about the same as initial values. Therefore, we have produced a orbital configuration that the outer planet has higher eccentricity than the inner planet by the interaction with the disc.

We found that the results are qualitatively about the same when we explore different values of parameters. Though we make the value of τ to be very small to save our computational time, it would not affect the final values of eccentricities.

5. Conclusions

The dynamics of extrasolar planetary systems continues to be a fascinating and important subject. One of the very

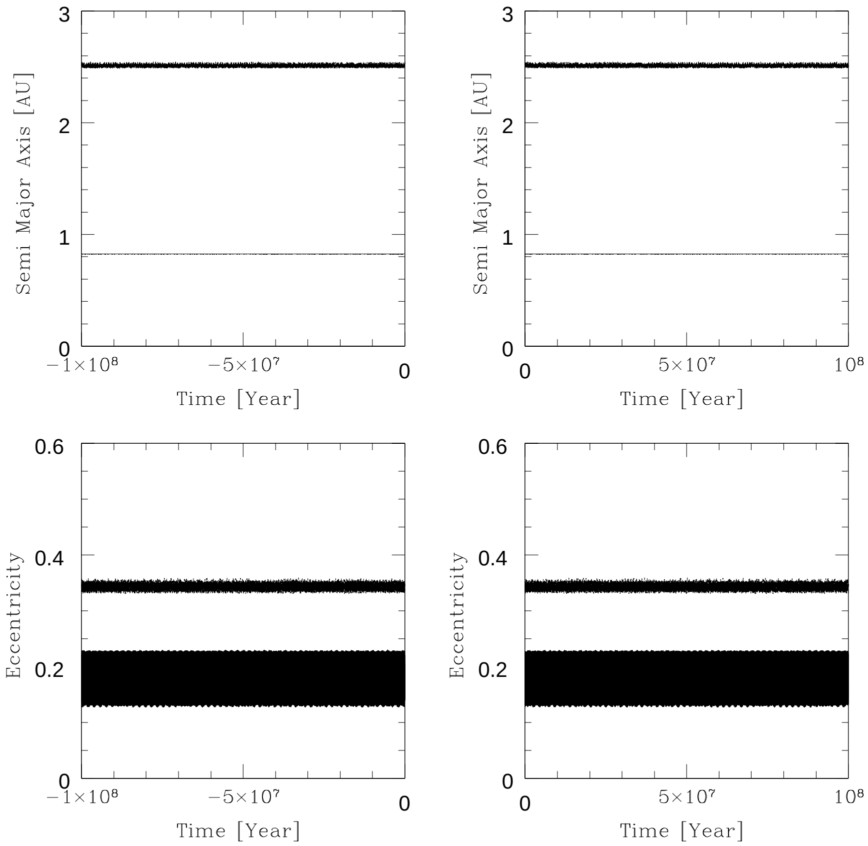

Fig. 3. The semi-major axes (top panels) and the eccentricities (bottom panels) of planets as function of time for both backward (left panels) and forward (right panels) integrations, where the solid line is for the middle planet, the dotted line is for the outer planet

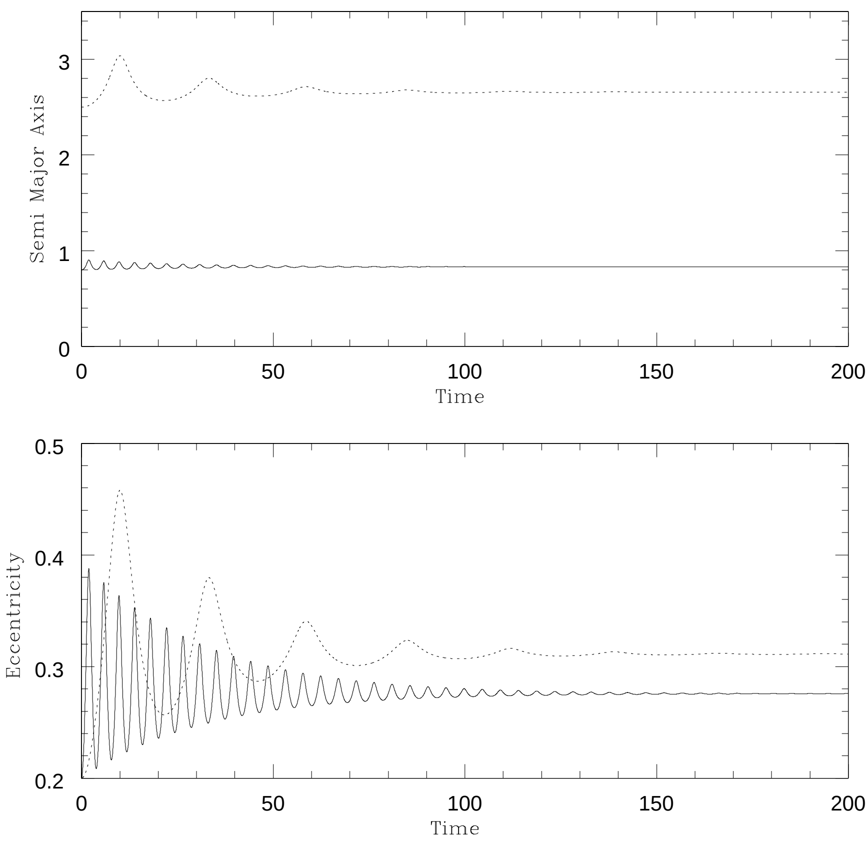

Fig. 4. The semi-major axes (top panel) and the eccentricities (bottom panel) of planets (under the interaction with the disc) as function of time, where the solid line is for the inner planet, the dotted line is for the outer planet

intriguing aspects for the extrasolar planets is the existence of orbits of high eccentricities. The dynamical cause of high eccentricities is unknown but should be related to the early history of planetary formation or stellar encounters.

Among these discovered extrasolar planetary systems, the upsilon Andromedae planetary system appears to be one of the most interesting one because of the presence of multiple planets and also the orbital configuration. Even though the cause of the high eccentricity of the outer planet of the upsilon Andromedae planetary system is not clear yet, our computation showed that the gravitational interaction of the four-body system is potentially very complex and the eccentricity of the middle planet oscillate between 0.125 and 0.225 over the time interval of orbital integration. The middle and the outer planets are indeed interacting strongly and the ignorance of the innermost planet can be a good approximation for the long-term integrations.

On the other hand, one general observational fact is that extrasolar planets with high eccentricities usually have larger semi-major axes than those with small eccentricities. The upsilon Andromedae planetary system follows this observational trend.

We investigate the origin of the current observed orbital elements of the upsilon Andromedae planetary system. Our long-term backward integration (order of Gyr) shows that the current orbital configuration was not caused by the orbital evolution because the orbital elements do not really change during the backward integration but just oscillate around the current values.

Our results show that the interaction between the exoplanets and the protostellar disc might lead to the current orbital configuration. It is possible that the model will be even more pertinent if there is energy dissipation when the planets interact with the disc. This energy dissipation might make the eccentricity of the inner planet decrease more than the outer planet would because there could be more dissipation around the inner disc. In this case, the eccentricity difference between two planets might be even larger. We hope to come back to this issue in the future.

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