The Roles of Discs for Planetary Systems

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ABSTRACT

It is known that the discs are detected for some of the extra-solar planetary systems. It is also likely that there was a disc mixing with planets and small bodies while our Solar System was forming. From our recent results, we conclude that the discs play two roles: the gravity makes planetary systems more chaotic and the drag makes planetary systems more resonant.

Key words: celestial mechanics – planetary systems – stellar dynamics

1 INTRODUCTION

More than 160 extra-solar planetary systems have been discovered so far and the number of detected exoplanets is likely to increase rapidly. This development has opened a new window for astronomers to investigate the planetary formation and evolution in detail. There are many numerical studies on the dynamical evolution of these detected systems (please see Laughlin & Adams 1999, Rivera & Lissauer 2000, Jiang & Ip 2001, Ji et al. 2002, Benest 2003).

Among these systems, the existence of discs seems to be a general phenomenon. For instance, there are asteroid belt and Kuiper belt for the Solar System, the discs of dust for extra-solar planetary systems and also circumbinary rings for binary systems. The disc or belt-like structure should influence the dynamical evolution of these systems. As mentioned in Jiang & Ip (2001), the origin of orbital elements of the planetary system of upsilon Andromedae might relate to the disc interaction. Moreover, Yeh & Jiang (2001) studied the orbital migration of scattered planets. They completely classify the parameter space and solutions and conclude that the eccentricity always increases if the planet, which moves on circular orbit initially, is scattered to migrate outward. Thus, the orbital circularization must be important for scattered planets if they are now moving on nearly circular orbits.

To concentrate on the dynamical role of discs for the planetary systems, Jiang & Yeh (2003, 2004a) did some analysis on the orbital evolution for systems with planet-disc interaction.

2 THE CHAOTIC ORBITS

Jiang & Yeh (2004b) studied the chaotic orbits for the disc-star-planet systems through the calculations of Lyapounov Exponent. Different initial conditions are used in the numerical surveys to explore the possible chaotic and regular orbits. They found that, in general, discs with different masses might change the sizes and locations of chaotic region. Some sample orbits are further studied and the plots of Poincaré surface of section are consistent with the results of Lyapounov Exponent Indicator. On the other hand, they pointed out that the influence of the disc can change the locations of equilibrium points and also the orbital behaviors. This point is particularly interesting. Without the influence from the disc, Wisdom (1983) showed that one of the Kirkwood gaps might be explained by the chaotic boundary. This is probably due to that the chaotic orbits are less likely to become resonant orbits. Indeed, the chaotic orbits in the disc-star-planet system shall play essential roles during the formation of Kirkwood gaps. For example, the disc might make some test particles to transfer from chaotic orbits to regular orbits or from regular orbits to chaotic orbits during the evolution.

The discs are often observed with various masses in both the young stellar systems and extra-solar planetary systems. It is believed that the proto-stellar discs are formed during the early stage of star formation and the planets might form on the discs through the core-accretion or disc instability mechanism. The planetary formation timescale is not clear but the gaseous disc will be somehow depleted and the dust particles will gradually form. The above picture is plausible but unfortunately the timescales are not completely understood. For a system with a star, planets, discs and asteroids, it is not clear what the order of different component’s formation is and what the duration of each component’s formation process would be.

Nevertheless, one thing we can confirm is that the discs are there and can have different masses at different stages. From our results, it is clear that the dynamical properties of orbits, i.e. chaotic or regular, can be determined quickly for different disc masses or models. Because those particles
moving on chaotic orbits might have smaller probability to become the resonant objects in the system, the Kirkwood gaps, which are associated with the location of mean motion resonance, in the Solar System might be formed by the dynamical effect we have discussed here. The detail processes would depend on the evolutionary timescale of the star, planet and also the disc. To conclude, it is important that the effect of discs on the chaotic orbits might influence the formation of the structures of planetary systems such as the Kirkwood gaps in the Solar System.

3 THE RESONANCE

The mean motion resonant relations between different celestial bodies are confirmed to be common phenomena for both Solar System and extra-solar planetary systems. For example, the gaps in the distribution of asteroids were connected to mean motion resonances by Kirkwood (1867) and known as Kirkwood gaps. Greenberg & Scholl (1979) classified the proposed explanations into four groups: the statistical hypothesis, the collisional hypothesis, the cosmogonic hypothesis, and the gravitational hypothesis. Dermott & Murray (1983) showed that there is a good correspondence between the width of the Kirkwood gaps and the width of the libration zone when the distribution of asteroid orbits is plotted in the $a - e$ plane. They concluded that the gravitational hypothesis was likely to be correct. This is completely consistent with the results on the chaotic orbits as we mentioned in the last section (Jiang & Yeh 2004b).

In addition to that, the small bodies at the outer Solar System, i.e. the Kuiper Belt Objects (KBOs), also show strong mean motion resonant relations with the Neptune’s orbit. It is surprising that about one-third of the KBOs are engaged into 3:2 resonance and are therefore called “Plutinos”. The sweeping mechanism proposed in Malhotra (1995) that the outward migration of Neptune might make the Plutinoses caught into 3:2 resonance. This mechanism could work under the condition that the Neptune’s orbit keep changing and thus the Neptune’s potential felt by the Plutinoses is time-dependent. This relative orbital movement might become negligibly small when the Neptune and KBOs are pushed out together. This scenario of pushing-out from the inner Solar System proposed by Levison & Morbidelli (2003) was to solve the KBOs’ formation issue since the density was higher in the inner Solar System and easier to form KBOs (and also Neptune). Moreover, Yeh & Jiang (2001) showed that the Neptune would be in an eccentric orbit if it was scattered outward. It will need a massive belt to circularize its orbit. Therefore, it is not clear that how the Plutinoses were captured into 3:2 resonance under the situation that the formation history of KBOs is unclear. Jiang & Yeh (2004c) proposed that the drag-induced resonant capture could play a role for this important process. (Please also see a brief review in Jiang & Yeh 2005.)

On the other hand, some extra-solar multiple planetary systems also show the resonances. For example, Ji et al. (2003) confirmed that the 55 Cancri planetary system is indeed in the 3:1 mean motion resonance by both the numerical simulations and secular theory. The GJ 876 and HD 82943 planetary systems are probably in 2:1 resonance as studied by Laughlin & Chambers (2001), Kinoshita & Nakai (2001), Ji et al. (2002) and Gozdziewski & Maciejewski (2001).

4 CONCLUDING REMARKS

The conventional models used in celestial mechanics consider the dynamical interactions between particles only. We take a first step to include the dynamical effect from the disc in the conventional celestial mechanics. In general, the disc shall vary with time. Nevertheless, in these studies, we only consider the orbital behaviors during a timescale shorter than the lifetime of the disc, the models shall give good implications for the first trend of orbital evolution under the disc potential. We find that when we consider the gravity only, there are more chaotic orbits when the disc is included. We also consider the effect of an artificial drag and find that the drag could bring particles into resonances. Our results’ general conclusion is consistent with the ones in Armitage et al. (2002) and Trilling et al. (2002), though they have different focuses, base on different approaches, and mainly study the gas-dynamical effects.

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