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A ROLE OF PROTO-ACCRETION DISK: HEATING PROTO-PLANETS TO EVAPORATION

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ABSTRACT

We study a role of the proto-accretion disk during the formation of the planetary system, which is motivated with recent X-ray observations. There is an observational correlation of the mass of extrasolar planets with their orbital period, which also shows the minimum orbital period. This is insufficiently accounted for by the selection effect alone. Besides, most of planetary formation theories predict the lower limit of semimajor axes of the planetary orbits around 0.01 AU. While the migration theory involving the accretion disk is the most favorable theory, it causes too fast migration and requires the braking mechanism to halt the planet $\sim$ 0.01 AU. The induced gap in the accretion disk due to the planet and/or the truncated disk are desperately required to stop the planet. We explore the planetary evaporation in the accretion disk as another possible scenario to explain the observational lack of massive close-in planets. We calculate the location where the planet is evaporated when the mass and the radius of the planet are given, and find that the evaporation location is approximately proportional to the mass of the planet as $m_p^{-1.3}$ and the radius of the planet as $r_p^{1.3}$. Therefore, we conclude that even the standard cool accretion disk becomes marginally hot to make the small planet evaporate at $\sim$ 0.01 AU. We discuss other auxiliary mechanisms which may provide the accretion disk with extra heats other than the viscous friction, which may consequently make a larger planet evaporate.

Keywords: planetary accretion disk, planetary formation, planetary evaporation

1. INTRODUCTION

Since the discovery of the first extrasolar planet around the pulsar PSR 1257+12 by using the pulsar timing analysis method (Wolszczan & Frail 1992), searching for extrasolar systems, particularly habitable planetary systems, becomes one of the most active research fields in observational astronomy. To date, there are $\sim$ 100 extrasolar giant planets known to be orbiting nearby main sequence stars (see http://exoplanets.org). The minimum masses ($M_p \sin i$) of these planets are ranging from fractions of a Jupiter mass (M_J) to 15 M_J. The semimajor axes of the planetary orbits range from $\sim$ 0.01 out to $\sim$ 4 AU. Such a Jovian planet may form at its current position, or form at another

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place and moves its position inward/outward to the present one. Interestingly enough, for semimajor axes less than 0.1 AU, however, there seems to be an observational lack of very massive planets (Marcy & Butler 2000, Zucker & Mazeh 2002). This is partly because of the detection limit for the radial velocity method (Perryman 2000). If, however, this is not wholly due to the observational bias, a formation theory for the planetary system should give an explanation for this apparent lack of massive close-in extrasolar planets (see Kenyon 2002 for review). For instance, Pätzold & Rauer (2002) explain the absence of massive planets at short distances by tidal interactions between planets and their central star that lead to a rapid decay of a planetary orbit toward the Roche lobe of the star within a short timescale. A higher metallicity of planet-bearing stars and the recent discovery of a ^{6}Li excess of a G0 star might further indicate that planets can indeed get lost in their host stars (Quillen & Holman 2000, Ryan 2000, Sandquist et al. 2002). Besides, any model that assumes migration driven by a planet-disk interaction can account for the deficit of massive planets with short periods, unless the planet masses do scale with their disk masses. Massive planets open a gap in the disk and consequently slow their migration rate substantially (Ward 1997, Trilling et al. 1998, Nelson et al. 2000). Or, migrating planets halt once this evacuated region contains the sites of their exterior 2:1 Lindblad resonances (Kuchner & Lecar 2002).

In this study, we explore the planetary evaporation as another scenario to explain the observational lack of close-in Jovian planets and investigate its feasibilities. It is motivated by a similar idea that planets can be evaporated while the star evolves through a giant phase (Soker 1998, Nelemans & Tauris 1998). They suggest the evaporation in order to explain the horizontal branch morphology and populations of a single under-massive white dwarf. Here, we are interested in roles of the accretion disk in the formation of the planetary systems, as seen in X-rays (Imanishi, Tsujimoto, & Koyama 2002, Kastner et al. 2002). The important difference is that the accretion disk around the parent star heats the proto-planet instead of the convective giant envelope. As estimated below, however, the temperature of the standard cool accretion disk is marginally high enough so that the evaporation process may occur. Therefore, other auxiliary heating mechanisms other than viscosity are required in the accretion disk in order that this mechanism pleasantly works.

2. BRIEF REVIEW OF THEORIES

There are three broad categories of the models for the existence of planets with short orbital period. The most favored model in a current stage is planetary migration due to the interaction with the disk. In this model, a planet is formed by core accretion at a distance of $\sim$ 5 AU or further and then is pulled toward the parent star by interactions with the accretion disk. Analytical calculations (Goldreich & Tremaine 1980, Ward 1997) and numerical simulations (Nelson et al. 2000, Kley et al. 2001, Armitage et al. 2002, D'Angelo et al. 2002, Rafikov 2002) suggest that proto-planets in a proto-planetary disk migrate rapidly into the star they orbit. Large proto-planets may open a gap in the disk via their resonant torques and thus become locked to the disk's gap. Sometimes an accreting planet may overflow its Roche lobe, losing mass to the star. And this process may halt the planet's migration (Trilling et al. 1998). Shu et al. (2001) review a theory of the interiors of proto-planetary disks that centers on the interaction between the stellar magnetic field and the inner edge of the conducting gas disk. In this theory, the disk is replaced by magnetic accretion columns and a bipolar wind interior to the truncation radius (Lin et al. 1996). Alternative models are migration by interaction with other planets (Weidenschilling & Marzari 1996) or planetesimals (Murray et al. 1998, 2002, Del Popolo et al. 2001, Del Popolo & Eksi 2002). The interactions among two planets and a star can leave a planet trapped by stellar tides in a circular orbit at $\sim$ 0.01 AU. This process was originally suggested mainly to explain the high eccentricities observed for some of the known extrasolar planets (Rasio & Ford 1996). The migration depends on the mass ratio between the planet and the planetesimal disk. The problem with gasless migration schemes is that substantially changing the orbit of a Jupiter-mass planet requires roughly a Jupiter mass of planetesimals. The third approach assumes planet formation by disk instability (Boss 1997, 2001). Obviously, if the instability ends up as a planet far away from the parent star, one needs a migration mechanism to account for the close-in planets.

3. PLANETARY EVAPORATION VIA ACCRETION DISK

One serious trouble of the migration model is that the migration occurs so rapidly that it is a wonder any planets survive at all. The migration model requires a gap in the disk or the truncated disk, as summarized in the last section. The position of the gap or the truncation, where planets may gather, is provided either by the mass of the planets and the disk (Trilling et al. 1998) or by the detailed model, e.g., with magnetic field (Lin et al. 1996, Murray et al. 1998, 2002, Kuchner & Lecar 2002). In this section we attempt to model the absence of the planet near the parent star without gap formation or truncations.

The T Tauri stars and Herbig Ae/Be stars are likely to host proto-planetary disks near the central star. The proto-planetary accretion disk is heated via viscosity or by irradiation of the central star. Particularly, observations of Herbig Ae/Be stars strongly suggest signs that proto-planetary disks may have passively heated inner walls (Natta et al. 2001, Dullemond et al. 2001, Dullemond et al. 2002). As a result of friction, and the large temperature difference between the accretion disk and the equilibrium temperature of the planet, the planet can be evaporated due to heating.

To model the effect of planetary evaporation we follow Soker (1998) and equate the local sound speed in the accretion disk to the escape velocity from the gaseous planet surface in order to find the approximate location of evaporation from the temperature:

$$c_s^2 \approx v_{esc}^2, \tag{1}$$

or,

$$\gamma \frac{k_B T}{\mu m_H} \approx \frac{2 G m_p}{\alpha r_p}, \tag{2}$$

where c_s is the sound speed, v_{esc} is the escape velocity on the surface of the planet, α is the efficiency of removing disk material which defines the rate of deposition of orbital energy of the planet into the ejected material of the disk, m_p and r_p are the mass and the radius of the planet, respectively, other constants represent usual meanings. The assumption that the evaporation occurs where the local sound speed in the accretion disk is equal to the escape velocity from the planet is justified by the results of Livio & Soker (1984). From Eq. (2) we have the evaporation temperature for a given (Jovian) planet

$$T \approx 3 \times 10^5 \, K \, \mu \left(\frac{m_p}{M_J} \right) \left(\frac{0.1 \, R_\odot}{r_p} \right), \tag{3}$$

where α is assumed to be an order of unity.

On the other hand, for a standard self-luminous disk via the viscosity (Shakura & Sunyaev 1973), the temperature is given as a function of the distance from the center:

$$T^4 = \frac{3 G M \dot{M}}{8 \pi \sigma r^3}, \tag{4}$$

where σ is the Stefan-Boltzmann constant, r is the distance from the central star, M is the mass of the central star, and $\dot{M}$ is the mass accretion rate of the disk. We estimate

$$T \approx 10^4\,K \left(\frac{M}{M_\odot}\right)^{1/4} \left(\frac{\dot{M}}{10^{-6} M_\odot \mathrm{yr}^{-1}}\right)^{1/4} \left(\frac{r}{0.01\mathrm{AU}}\right)^{-3/4} . \tag{5}$$

By equating eqs. (3) and (5), we may calculate the location where the planet is evaporated when the mass and the radius of the planet are given. We note that the evaporation location, $a_{\rm evap}$, is approximately proportional to the mass of the planet as $m_p^{-1.3}$ and the radius of the planet as $r_p^{1.3}$. Therefore, as long as the mass of the planet is slightly smaller than that of the Jupiter and/or the radius of the planet is a bit larger, the evaporation may occur at $\sim$ 0.01 AU. However, it is fair to point out that for our own Jupiter-like planet the evaporation should occur at the small distance to the star. Of course, the accurate estimate also requires the mass accretion rate and the mass of the central parent star.

4. DISCUSSION AND CONCLUSION

Using a temperature profile for the accretion disk, we have considered that the planetary evaporation may occur at an observational cutoff of the semimajor axis. Solving the above equations, with the temperature dependence given above, yields the location of the evaporation as a function of the mass and the radius of the planet. Planets less massive than m_{crit} will evaporate completely, where the estimated evaporation location turns out to be the radius of the star. To calculate the evaporation location more accurately, the physical condition of the planet during the capture should be taken into account. For instance, during the spiral-in the radius of a giant planet may increase slightly even though only a small amount of mass is believed to be accreted. If the planet becomes significantly swollen, it is more likely to be evaporated.

The accretion disk can be hotter than the standard cool disk we use in the model. A case one may imagine is the irradiated disk case. As studied for the flaring disk (Chiang & Goldreich 1997), one may consider the case where the inner part of the disk is removed where the inner edge is directly irradiated by the parent star. The accretion disk can be truncated by the magnetic field of the parent star. In this case, the inner rim is heated and the heat is diffused into the accretion disk so that the disk has an extra source of heating. The detailed calculation of the temperature also requires the opacity of the disk. Magnetic reconnection leading to magnetic flares may also help to heat the disk (e.g., Shu et al. 2001, Liu et al. 2002). Lastly, the intrinsically hot disk may exist rather than the cool disk we used for the model (Abramowicz et al. 1995, Chang 2001, Yuan 2001, Ohsuga et al. 2002). If the disk is so optically thick that the radiation cannot escape freely, the temperature can be higher. One may further consider a rather radical idea of the nucleosysthesis inside the accretion disk (Fujimoto et al. 2001). Therefore, our estimate of the disk temperature can be regarded as the minimum temperature of the disk that may heat the planet to evaporation.

In conclusion, we calculate the evaporation location where the planet is evaporated and find that the evaporation location is approximately proportional to the mass of the planet as $m_p^{-1.3}$ and the radius of the planet as $r_p^{1.3}$, when the mass and the radius of the planet are given. We conclude that even the standard cool accretion disk becomes marginally hot to make the small planet evaporate at $\sim$ 0.01 AU. This conclusion is strengthened by the fact that other heating sources are likely in the accretion disk which may provide the accretion disk with extra heats other than the viscous friction, which may consequently make a larger planet evaporate.

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