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Does Si Play a Role in the Formation of Extrasolar Planet Systems?

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Abstract. With the high signal-to-noise ratio spectra, we obtained Si abundances of 22 extrasolar planet host stars, and discussed some constraints on the planet formation. Using our silicon abundance results and other authors' Si abundance studies about planets-harboring stars, we investigated the correlation between the dynamical properties and the silicon abundance. We propose a hypothesis that higher primordial metallicity in the host stars' birth cloud with higher abundance of Si will make the cloud more sticky to bypass the time scale restriction in planet formation and easier to form the planets.

Key words. Planetary systems: formation—stars: abundances—stars: late-type.

1. Introduction

From the first discovery of extrasolar planet host system (Mayor & Queloz 1995), there are about 200 planet-harboring systems which have been found. Most of them are discovered by using the Doppler technique. One of the key factors which is relevant to the mechanism of planetary formation is that many such systems are really metal-rich (e.g., Gonzalez *et al.* 2001; Smith *et al.* 2001; Sadakane *et al.* 2003) compared with the metallicity distribution of nearby field F, G, or K stars which are known to hold non-planets. Gonzalez (1997, 1998) proposed two hypotheses to account for the correlation between metallicity and the presence of the giant planets: the first view shows that higher primordial metallicity in the host stars' birth cloud helps planets to be more easily or efficiently formed (e.g., Pollack *et al.* 1996). The second view proposed that the observed high metallicity may be the result of a "self-enrichment" process. Accretion of high-Z material after the outer convection zone of the host star has thinned to a certain minimum mass, elevates the apparent metallicity above its primordial value. Some studies (see, e.g., Takeda *et al.* 2001; Sadakane *et al.* 2002, 2003; Fischer & Valenti 2005; Huang *et al.* 2005a, 2005b; Shen *et al.* 2005) show that there exists no significant evidence to prove the "self-enrichment" hypothesis.

This work discusses the time-scale constraints in planet formation and presents the correlation between dynamical properties and silicon abundances. We try to examine the "high primordial metallicity" hypothesis from a special point of view that metal-silicon relationship leads to fast planet formation.

2. The constraints in planet formation

According to the standard model of planet formation, when the dust settles to the midplane of the disk, grains coagulate and grow to small (1–10 km diameter) planetesimals. The planetesimals accumulate and accrete the gas to form terrestrial or giant planets. So there exist two stages in planet formation. During the first stage, dust to planetesimals, there exist interactions with the gas dominating. The gravity influence is neglectable. In the second stage, planetesimals to planets, gravity plays the bigger role.

2.1 *The stage of dust to planetesimals*

For the early solar-like nebula, the most abundant condensates are silicates and iron compounds. These initial micron-sized grains are believed to form the planetesimals by inelastic collisions. The grain growth process is determined by the sticking efficiency upon collisions (Poppe *et al.* 2000). The principal problem (Wetherill 1990) in this stage appears to be the need to grow fairly large (> 10 m) planetesimals before the time the nebular gas is removed (3–10 Myr, Hartmann 1998). The characteristic settling time of a 1-μm grain will be 2.9×10^6 yr (Wetherill 1990). This time is too long compared to the time scale for the removal of the gas in the solar-like nebula and the turbulences will lengthen the settling time. Another problem is that the large particles will encounter a headwind which will cause their angular momentum loss and they will spiral inward towards the host star (Weidenschilling 1977). These particles should complete the transition from cm size to km size rather rapidly, especially for m-size particles, otherwise the material will not survive to form the planets (Lissauer 1993). However, the growth of solid bodies from mm-size to km-size still presents particular problems. There must be some way to increase the efficiency of the planetesimal formation.

2.2 *The stage of planetesimals to planets*

The early version of gas giant formation model provides a constraint that 10–20 $M_\oplus$ cores are needed to initiate efficient gas accretion (Pollack *et al.* 1996). The gas giant formation time scale is critical because the gas giant almost consists of hydrogen and helium, the gaseous solar-like nebula still being present when the gas giant began to form (Wetherill 1990). According to the present studies, the observed disk depletion time scale is 3–10 Myr (Walter 1986; Strom *et al.* 1989; Hartmann 1998). For the reasons above, the massive core must form rapidly in order to initiate gas accretion while the nebular gas is still available. So the planetesimals should find an efficient way to accumulate.

3. Results and discussion

3.1 *Data*

We obtained the silicon abundances of 22 samples from our new article (Huang *et al.* 2005a) and chose an other 59 samples from previous studies (Gonzalez *et al.* 2001;

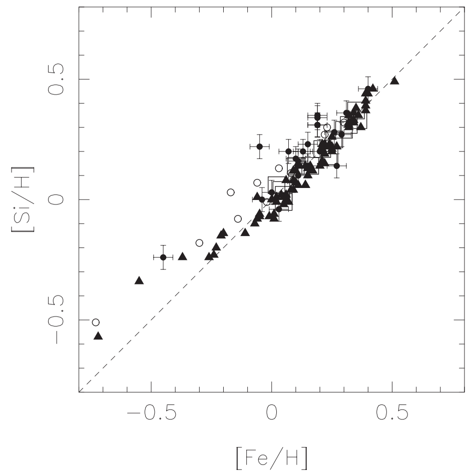

Figure 1. Plot of [Si/H] *vs.* [Fe/H]; our results of 22 samples with error bars are denoted by black points, the results from Gonzalez *et al.* (2001) are designed by hollow squares, data of the results from Bodaghee *et al.* (2003) are shown by black triangles, results from Sadakane *et al.* (2002) are shown by open circles.

Sadakane *et al.* 2002; Bodaghee *et al.* 2003). In Fig. 1, we plot [Si/H] *versus* [Fe/H], they have a good one-to-one correlation. It means the initial cloud with high primordial metallicity will have high primordial silicon abundance and more silicates. Our results of [Si/H] show the average of 0.06 dex higher than those that overlap in Bodaghee *et al.* (2003), the [Si/H] results from Sadakane *et al.* (2002) and Gonzalez *et al.* (2001) show a slight higher and a bit lower than the same samples in Bodaghee *et al.* (2003), respectively. The average values of [Si/H] are 0.12, 0.20, 0.19, 0.05, which are respective to 78 samples of Bodaghee *et al.* (2003), 22 samples of ours, 13 samples of Gonzalez *et al.* (2001), 12 samples of Sadakane *et al.* (2002). Si is a dominant element in the component of the Earth and silicates are good adhesive material in some circumstances.

3.2 *Discussion on the constraints*

Robinson *et al.* (2006) suggested that silicon and oxygen are both α elements and [Si/Fe] is a tracer of [O/Fe], so a silicon-enrich star implies an oxygen-rich star. The oxygen-rich star will increase the solid surface density and make more ice cores to form the planets. We discuss this correlation of Si-rich and planets from another point of view. We suppose that the Si-rich primordial cloud implies an Si-rich and O-rich cloud, so this type of cloud will make more silicates to increase the "stickness" of the cloud and be easy to form planets.

In section 2.1, if the dust settling proceeds more rapidly, the grain should grow larger. Grossman (1988) found chondrules of $\sim$ 1-mm radius in most stony meteorites. To mm-size particles, the corresponding settling time will be shortened to $\sim 3 \times 10^3$ yr (Wetherill 1990). According to their calculations, Kornet *et al.* (2004) reported that if the main process responsible for particle growth is collisional coagulation, then its efficiency should be high. The recent observations by Chakraborty *et al.* (2004) show that asteroid-size bodies can exist in disks as young as 0.1 Myr, that means if their growth is due to the coagulation, the sticking efficiency must be very high. In accordance with the contact model (Johnson *et al.* 1971), the adhesive surface forces will increase the contact radius and the sticking probability. We suppose the cloud with high primordial silicon abundance could increase the sticking efficiency of particles that makes the km-size planetesimals form in the dust settling time $\sim 10^4$ yr.

In the early stage of planetesimal accumulation, the rate of growth of planetesimal increases as $\sim R^2$, where R is the radius of the growing body (see details in Lissauer 1993), and the gravity influence is weak. Hence, the runaway growth starts slowly and the surface property is important to the encounters. It appears that the "stickiness" is necessary in colliding cases during this stage. We assume that more silicates could influence the sticking efficiency of colliding bodies in the early stage of planetesimal accumulation and change the size of planetesimals in the early phase of runaway growth. It is possible that the "initial" size distribution of planetesimals significantly influences the growth times of the giant planets (Lissauer 1993). For example, it will cost the protoplanet $\sim 6 \times 10^5$ years to attain 15 M⊕ (Lissauer 1987).

3.3 *Dynamical properties discussion*

The disk gas will be evaporated either through photo-evaporation or driven by central stars from the inner disk region (Hollenbach & Adams 2004) during a period of relative fixed time. So if the initial cloud has an efficient way to form planets, the situation of the disk gas will give a reflection of the giant planets' orbital properties. In Fig. 2, we plot 81 samples' orbital properties with their silicon abundance. We suppose that if the giant planet forms rapidly, it will increase the possibility to present itself near the central star or migrate to the central star when the gas at inner region is still available. The top diagram shows a slight decreasing trend of [Si/H] with increasing semimajor for our 22 samples when semimajor a $<$ 3 AU. However, there is a large scatter in other samples. Maybe the scatter is caused by the stochastic events in the planet formation and the different results used by investigators. The mass of giant planet is dominated by gas, so [Si/H] should not be relevant to the mass. The middle diagram shows no obvious trend of [Si/H] with the mass. The bottom diagram shows a decreasing trend of [Si/H] with increasing eccentricity for our 22 samples and 13 samples from Gonzalez (2001). Despite the large scatter, the results from Bodaghee *et al.* (2003) also show the mimic trend. We obtained the slope by a linear least-squares fit for [Si/H] *versus* the eccentricities of our 22 samples in the bottom panel of Fig. 2, and the slope value is near -0.24. Though the straight-line fit to [Si/H] *versus* the eccentricities is not meant to imply that there is a real linear relation between [Si/H] and eccentricities, it is used to characterize the [Si/H] distribution by the slope with the value of -0.24. Small eccentricities are a requirement of the standard model for the formation of a giant-planet in the scenario of gradual accretion of solid particles in a disk and followed by gravitational accretion of gas (Smith *et al.* 2001). So the bottom diagram implies that maybe the initial cloud with high primordial silicon abundance adapts to forming giant planets. We suppose the inner disk gas will exist to influence the planets' eccentricities in the planet migration because the planet can form efficiently in the initial Si-rich cloud. However, it is difficult to quantify this scenario for lots of details in this process are obscure.

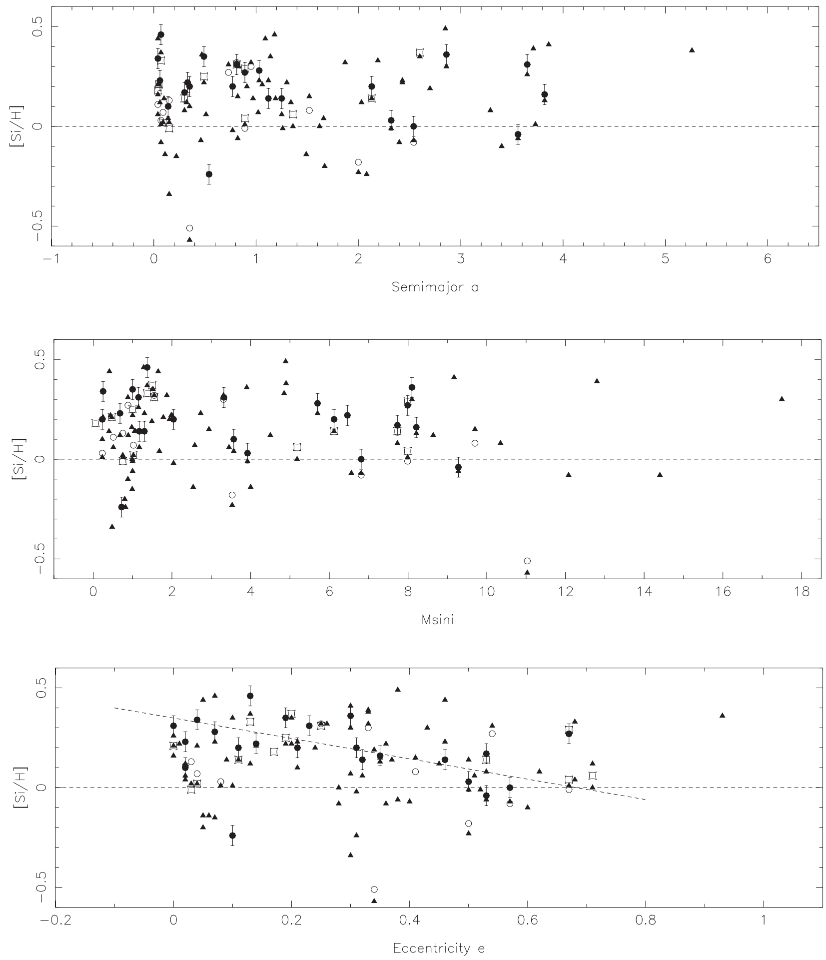

Figure 2. The trend of dynamical properties: (Semimajor a, Msini, eccentricity e) with [Si/H], symbols in figures are the same as in Fig. 1.

To investigate the two-order effects, we plot the relative abundances of [Si/Fe] *versus* the various planetary parameters in Fig. 3. The top diagram and the middle diagram in Fig. 3 show that the planet-host stars with high [Si/Fe] have planets of short-period orbits and small companion masses. The whys about the lack of short-period massive planets is that massive planets finish forming too late to experience the Type II migration (after opening the gap in the disk) which would cause the massive planets to get near to their central stars (Udry *et al.* 2003). The facts imply that maybe the [Si/Fe]-high cloud would not be easy to form massive planets. The extrasolar planet systems' discoveries may be influenced by the selection effects. However, most of the [Si/Fe]-rich planet hosts gather inside 1 AU of semimajor and their companies' masses are less than 4 Jupiter-masses. The semimajors and the companies' masses ranges are beyond the selection effect influence, so the results should not be caused by the selection effects of observation. In the bottom panel in Fig. 3, our results show that the planet-host stars with high [Si/Fe] are likely to have planets of small eccentricities,

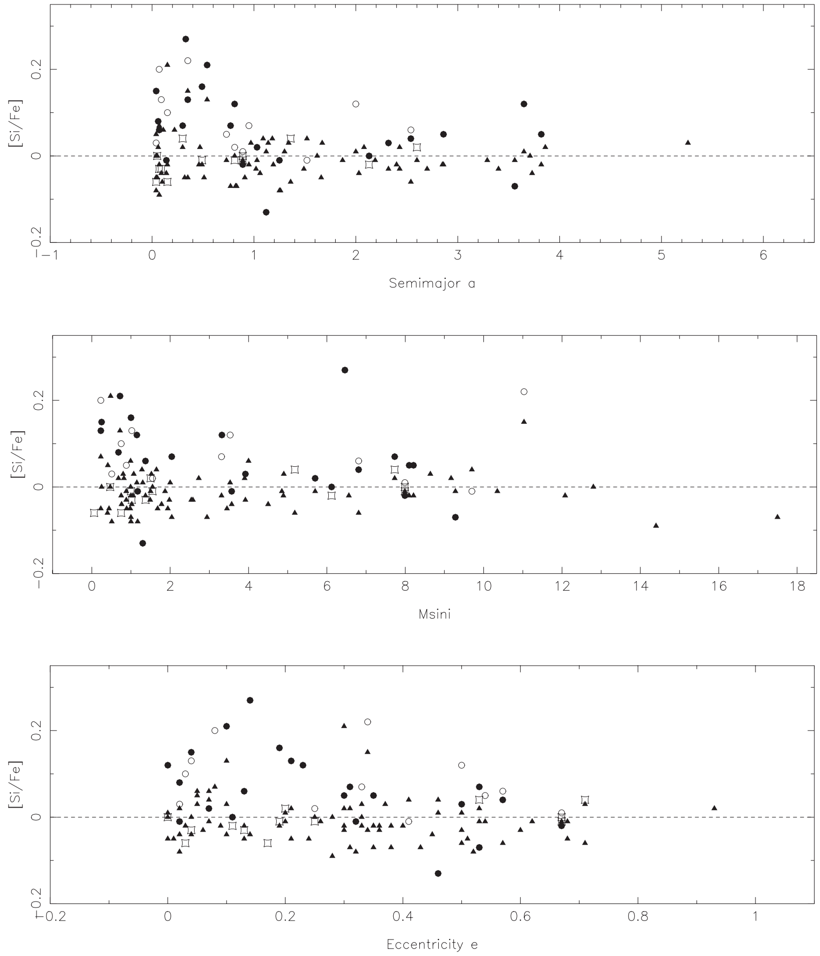

Figure 3. The trend of dynamical properties: (Semimajor a, Msini, eccentricity e) with [Si/Fe], symbols in figures are the same as in Fig. 1.

but there is a large scatter in [Si/Fe] *versus* eccentricity in other studies. So we cannot draw a firm conclusion.

4. Concluding remarks

Calculations reported by Kornet *et al.* (2005) show that the disk viscous coefficient will influence the rate of the planet occurrence. A too high viscous coefficient will reduce the rate of the planet occurrence. Maybe that can explain why the relative frequency of planet hosts has a sharp cutoff when the metallicity reaches 0.4 dex (Israelian 2004). As one might expect, in the disk with [Fe/H] > 0.5, there are more silicates which make the disk viscous coefficient too high to let the star associated with planets. Robinson *et al.* (2006) reported that the planet-host stars exhibit statistically significant silicon enrichment in their observations, their simulations predict the important relationship of the silicon enrichment with the core-accretion model for the giant planet formation and they discussed the origin of the planet-silicon correlation in planet-host stars. The observations hint that the planets may be easily formed in the silicon-rich cloud.

We investigate the dynamical properties of 81 extrasolar planet systems with the corresponding silicon abundances and discuss the time scale constraints in planet formation. According to the investigation, we propose a hypothesis that the initial cloud with high primordial metallicity may have high primordial silicon abundance and more silicates which make the cloud more sticky to form the planets efficiently, but to the disk with [Fe/H] > 0.5, nature will tune the effect of silicates to the contrary. However, this study still stays at the qualitative "scenario" stage. There exists a number of obscure problems and further quantitative studies are desirable.

Acknowledgements

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References

Bodaghee, A., Santos, N. C., Israelian, G., Mayor, M. 2003, *A&A*, **404**, 715.
Chakraborty, A., Ge, J., Mahadevan, S. 2004, *ApJ*, **606**, L69.
Fischer, D. A., Valenti, J. 2005, *ApJ*, **622**, 1102.
Gonzalez, G. 1997, *MNRAS*, **285**, 403.
Gonzalez, G. 1998, *A&A*, **334**, 221.
Gonzalez, G., Laws, C., Tyagi, S., Reddy, B. E. 2001, *AJ*, **121**, 432.
Grossman, J. N. 1988, Formation of chondrules (Tuscon: Ariz Univ. Press).
Hartmann, L. 1998, Accretion Processes in Star Formation (Cambridge: Cambridge Univ. Press).
Hollenbach, D., Adams, F. C. 2004, *ASP Conference Series*, Vol. **324**, p. 168.
Huang, C., Zhao, G., Zhang, H. W., Chen, Y. Q. 2005a, *MNRAS*, **363**, 71.
Huang, C., Zhao, G., Zhang, H. W., Chen, Y. Q. 2005b, *Chinese J. Astron. Astrophys.*, **6**, 619.
Israelian, G. 2004, *IAUS*, **219**, 343.
Johnson, K. L., Kendall, K., Roberts, A. D. 1971, *Proc. Roy. Soc. London A*, **324**, 301.
Kornet, K., Stepinski, T. F., Rozyczka, M. 2004, *A&A*, **417**, 151.
Kornet, K., Bodenheimer, P., Rozyczka, M., Stepinski, T. F. 2005, *A&A*, **430**, 1133.
Lissauer, J. J. 1987, *Icarus*, **69**, 249.
Lissauer, J. J. 1993, *ARA&A*, **31**, 129.
Mayor, M., Queloz, D. 1995, *Nat*, **378**, 355.
Pollack, J. B., Hubickyj, O., Bodenheimer, P. *et al.* 1996, *Icarus*, **124**, 62.
Poppe, T., Blum, J., Henning, T. 2000, *ApJ*, **533**, 454.
Robinson, S. E., Laughlin, G., Bodenheimer, P., Fisher, D. 2006, astro-ph/0601656.
Sadakane, K., Ohkubo, M., Takeda, Y. *et al.* 2002, *PASJ*, **54**, 911.
Sadakane, K., Ohkubo, M., Honda, S. 2003, *PASJ*, **55**, 1005.
Shen, Z. X., Jones, B., Lin, D. N. C., Liu, X. W., Li, S. L. 2005, *ApJ*, **635**, 608.
Smith, V., Cunha, K., Lazzaro, D. 2001, *AJ*, **121**, 3207.
Strom, K., Strom, S. E., Edwards, S. *et al.* 1989, *AJ*, **97**, 1451.
Takeda, Y., Sato, B., Kambe, E. *et al.* 2001, *PASJ*, **53**, 1211.
Udry, S., Mayor, M., Santos, N. C. 2003, *A&A*, **407**, 369.
Walter, F. M. 1986, *ApJ*, **306**, 573.
Weidenschilling, S. J. 1977, *MNRAS*, **180**, 57.
Wetherill, G. W. 1990, *Annu. Rev. Earth Planet. Sci.*, **18**, 205.