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An Analysis of the Condensation Temperature of Elements of Extrasolar Planetary Systems *

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Abstract Using high signal-to-noise ratio spectra of extrasolar planet-hosting stars, we obtained the atmospheric parameters, accurate metallicities and the differential abundance for 15 elements (C, O, Na, Mg, Al, Si, S, Ca, Sc, Ti, V, Cr, Mn, Ni and Ba). In a search for possible signatures of metal-rich material accreting onto the parent stars, we found that , for a given element, there is no significant trend of increasing [X/H] with increasing condensation temperature $T_{\rm c}$. In our sample of planet-harboring stars, the volatile and refractory elements behave similarly, and we can not confirm if there exists any significant dependence on the condensation temperature $T_{\rm c}$.

Key words: planetary systems — stars: abundance — stars: late-type

1 INTRODUCTION

The total number of planet-harboring systems found by using Doppler technique is approaching 136. One of the key findings which is relevant to the mechanism of planetary formation is that many such systems are really metal-rich (see, e.g., Gonzalez et al. 2001; Santos et al. 2001; Smith et al. 2001; Sadakane et al. 2003; Santos et al. 2004) when compared with the metallicity distribution of nearby field F, G, or K stars that are known to have no planets. Gonzalez (1997, 1998) proposed two hypotheses to account the correlation between the metallicity and the presence of the giant planets: the first is that a higher primordial metallicity in the host star's birth cloud makes planets more easily or efficiently formed (see e.g., Pollack et al. 1996); the second proposes that the observed high metallicity may be the result of a "self-enrichment" process, that accretion of high-Z material after the outer convection zone of the host star has thinned to a certain minimum mass raises the apparent metallicity above its primordial value.

There is a clue for checking the "self-enrichment" hypothesis. For if the accretion occurred in a relatively high temperature environment, then refractory elements would have been added

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preferentially compared to volatile elements. In other words, light elements, such as C, N, and O, which are known to condense at relatively low temperature (volatile elements) are expected to behave differently compared to those elements such as the iron-group elements (refractory elements). This process is expected to occur when the infall is slow enough for the volatile elements to have sufficient time to evaporate. If significant accretion of H- and He-poor materials occurred, there might be fractionation pattern in the accreted matters. On the other hand, when the enrichment is done rapidly by the infall of large bodies such as planets, chemical differentiation will not occur substantially because fractionation will not happen in this case. This idea was initially explored by Gonzalez (1997). Smith et al. (2001) examined the observed abundance patterns against the condensation temperature, and found a small group of stars with planets that shows a positive slope in the [X/H] versus T_c diagrams. Takeda et al. (2001) found no sign of such a trend in their analysis of the abundances of five volatile elements (C, N, O, S and Zn) in 14 stars with planets. Sadakane et al. (2002, 2003) found no significant signature between [X/H] and T_c with their sample of 12 planet-hosting stars. The question whether there is any systematic difference in the abundances of volatile and refractory elements in the parent stars is still open.

This work presents the correlation of [X/H] and T_c for 22 extrasolar planet-hosting stars, in order to settle these complicated issues. It is interesting to explore the detailed abundance pattern in these 22 stars and to examine the possible connection between the chemical abundances and the formation of planets. For each star we analysed the abundances of 15 elements against T_c.

2 OBSERVATIONS AND DATA REDUCTIONS

Spectroscopic observations of 22 planet-harboring stars were carried out with the 2.16 m telescope at the National Astronomical Observatories (Xinglong, China) with the coudé echelle spectrometer. Our observation covered the red spectral region (560 nm $< \lambda <$ 900 nm). The spectrum's signal-to-noise ratio is from 150 to 250. Technical details of the spectrograph are described in Zhao & Li (2001).

The reduction of the two-dimensional echelle spectral data (bias subtraction, flat-fielding, scattered-light subtraction, extraction of spectral data and wavelength calibration) was performed using the MIDAS software package, following the standard routines. Measurements of equivalent width for metallic lines were carried out using two different methods: direct integration of the line profile and a Gaussian function fitting. The final equivalent widths were estimated from these two measurements, depending on the line intensity (Zhao et al. 2000).

3 ABUNDANCE ANALYSIS

We measured the effective temperature from the Strömgren photometric indices (Olsen 1983, 1993) using the calibration by the infrared flux method (Alonso, Arribas & Martinez-Roger 1996), and calculated the surface gravity from accurate *Hipparcos* parallaxes (ESA, 1997). The microturbulence, ξ_t, was determined from the abundance analysis by requiring a zero slope of [Fe/H] versus equivalent width. Finally, the whole procedure of deriving T_eff, $\log g$, [Fe/H], and ξ_t was iterated till consistency. The atmospheric parameters of the 22 extrasolar planet host stars, along with the *Hipparcos* parallax and its error, mass, bolometric correction, and their color index $b-y$, are presented in table 1 of Huang et al. (2005).

Abundances for all elements were derived in standard LTE model atmospheres taken from Kurucz (1993) using the program, ABONTEST, which was kindly supplied by Dr. P. Magain (Liége, Belgium). The $\log gf$ values we used in this work are mostly taken from Chen et al. (2000, table 4), the $\log gf$ value of C I 658.7 nm was taken from Vienna Astrophysical Line

Data-Base[1], and the *gf* values of S I 604.6 nm and 605.2 nm were taken from Santos, Israelian & Mayor (2000). We estimated the errors of the derived abundances from the uncertainties of stellar parameters. Our calculation of Sc and Mn abundances takes into account the HFS (the hyperfine structure) effect. Details of these sample stars' chemical abundances can be found in Huang et al. (2005).

The condensation temperature data were taken from the Lodders (2003) table of T_c value for a solar composition at a pressure of 10^{-4} bar. Conditions may affect the absolute values of T_c, but it is negligible for the relative order of elements shown in Figure 1.

4 RESULTS AND DISCUSSION

We examine the relation between [X/H] and the condensation temperature (T_c) in order to check for possible signature of accretion of metal-enriched materials by potential planet-hosting stars. We present our results for the 22 sample stars in Figure 1. We plot the observed values of [X/H] against T_c for each star, and obtained the slope by a linear least-squares fit for each panel in Figure 1 in order to quantify the behavior of the [X/H] and T_c relation for each star. However, the straight-line fitting is not meant to imply that there is a real linear relation between [X/H] and T_c: it is used simply to characterize the abundance distribution by a single number — the slope, T_{cp}. For HD 23596 we have a negative slope, $T_{cp} = -24.39 \pm 1.92 \times 10^{-5}$ dex/K, which is consistent with the values found in metal-poor field F, G stars as noted in Smith et al. (2001). It is a discrepancy to the hypothesis of "self-enrichment". Smith et al. (2001) analysed published abundance data of planet-harboring stars given in Gonzalez et al. (2001), and found largest positive [X/H] versus T_c slopes in five stars. We have 10 stars in common with their study: HD 9826, HD 10697, HD 16141, HD 37124, HD 46375, HD 52265, HD 89744, HD 168443, HD 210277 and HD 217107. Three stars, HD 52265, HD 89744 and HD 217107, have the largest values of T_{cp} in the results of Smith et al. (2001). The slope values of [X/Fe]-T_c for these three stars are $(2.54 \pm 2.15) \times 10^{-5}$, $(7.88 \pm 2.55) \times 10^{-5}$ and $(5.33 \pm 3.10) \times 10^{-5}$ dex/K, respectively in our study, smaller than the results (14×10^{-5}, 17×10^{-5} and 12×10^{-5} dex/K) given in Smith et al. (2001). We list the slopes T_{cp} for all the stars in Table 1. Most of them are smaller than $10 \pm 1.0 \times 10^{-5}$ dex/K. There is no significant trend or any significant positive slope in our sample stars. Takeda et al. (2001) obtained similar results after examining the relation between [X/H] and T_c for 14 bright planet-harboring stars and Sadakane et al. (2002) obtained a similar conclusion from their sample of 12 planet-harboring stars. We estimate that the influence of abundances' error is small in the calculation of T_{cp}, and it may be neglected in this study. Details of the errors in the abundances can be found in table 2 of Huang & Zhao (2005).

Based on the model of D'Antona & Mazzitelli (1994), the thickness of the convective envelope decreases with increasing mass and becomes nearly zero above $1.15\,M_\odot$. Since thinner convective envelopes are more easily polluted in the "self-enrichment" model, one would find a dependence of the star's mass on the T_{cp}s. Refractory and volatile elements might provide more significant evidence of fractionation in more massive stars being associated with thinner convection zones. If accretion really occurred, there may be some correlation between the star's mass and the corresponding T_{cp}, or between the star's mass and the corresponding metallicity. Concentrating on Figures 2 and 3, the star masses are estimated using stellar evolutionary tracks and we did not obtain any obvious trend in the two diagrams despite their scatter. However, the thickness is easily influenced by the value of mass. An uncertainty of $0.1\,M_\odot$ will change the convective envelope thickness by a factor of several units. So it is too early to draw a firm conclusion. In Figure 4 we plot [Fe/H] versus T_{cp} for 22 sample stars. Despite the large scatter, T_{cp} increases with the metallicity. This trend is caused by Galactic chemical evolution,

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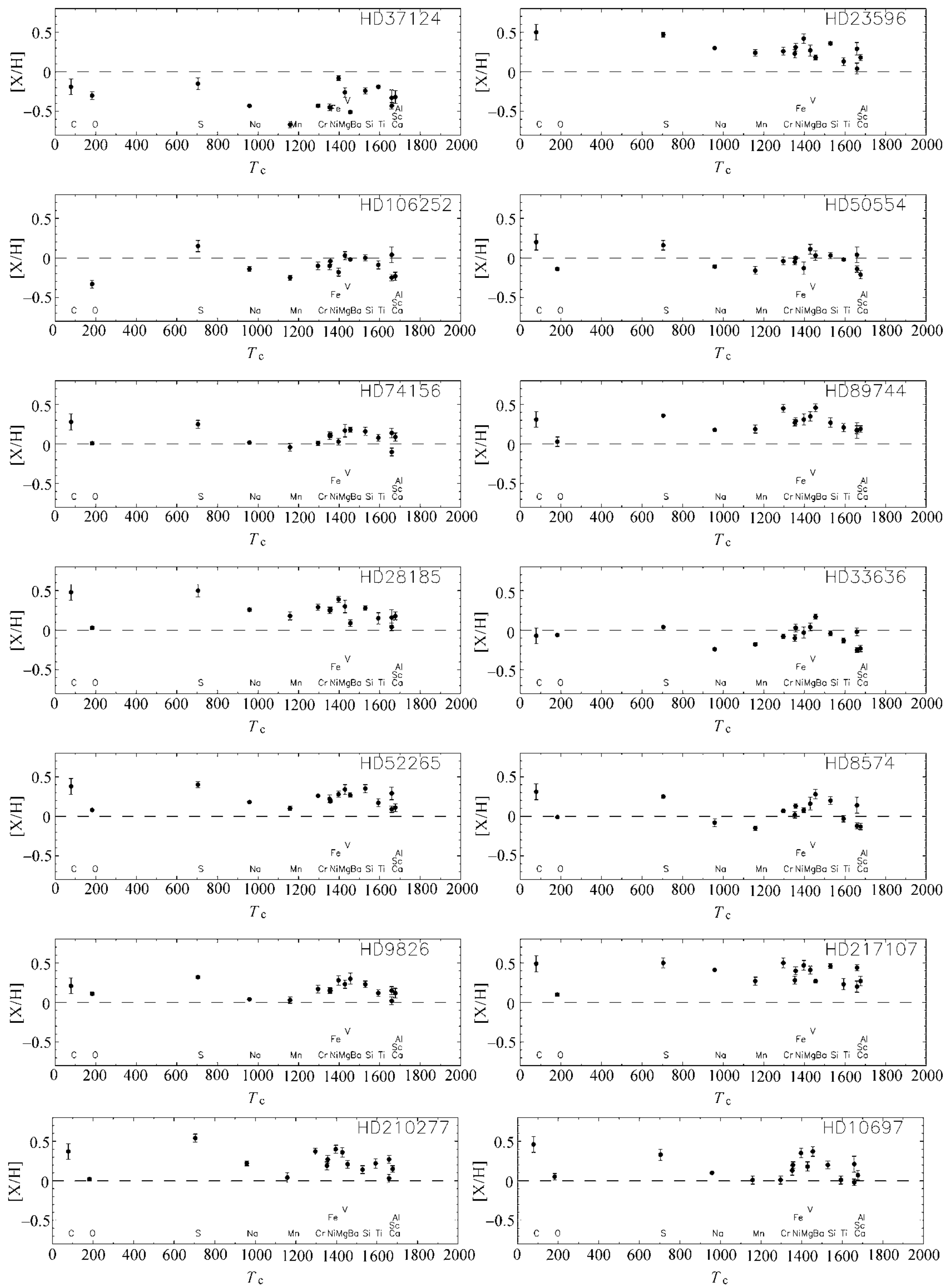

Fig. 1 Abundances, relative to the solar values, for each star as functions of the elemental condensation temperature, T_c.

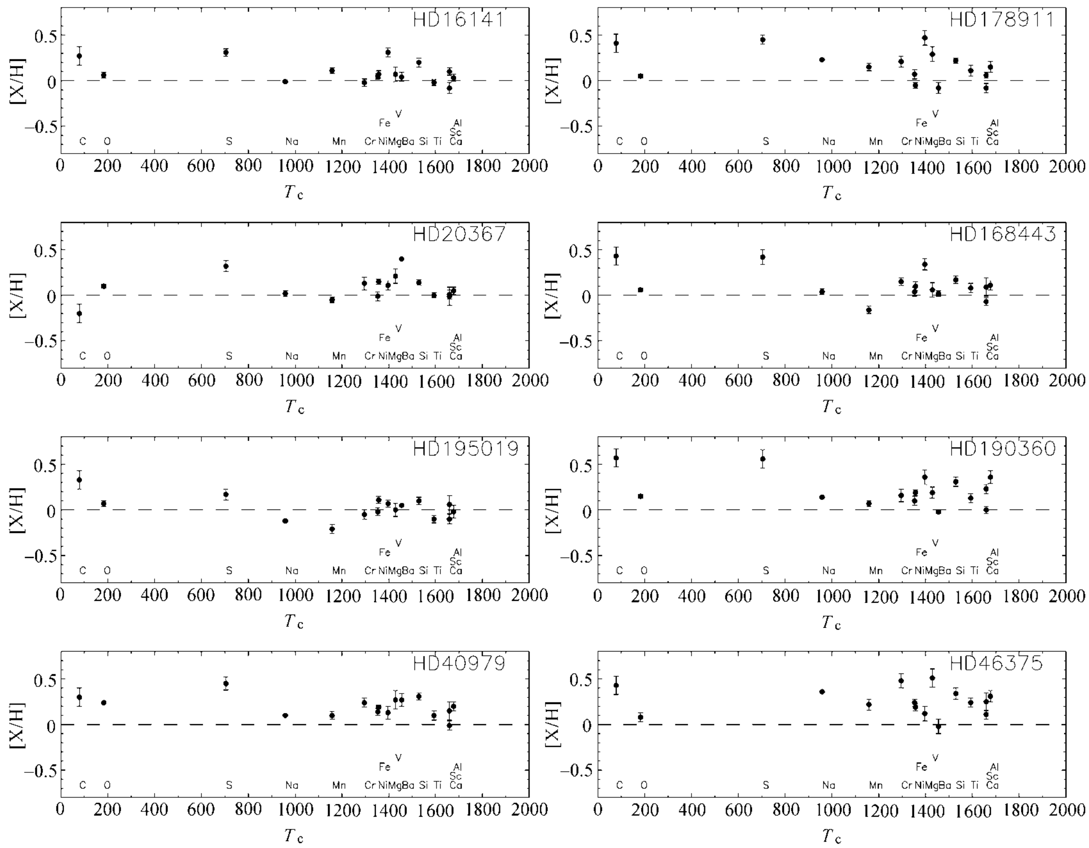

Fig. 1 Continued.

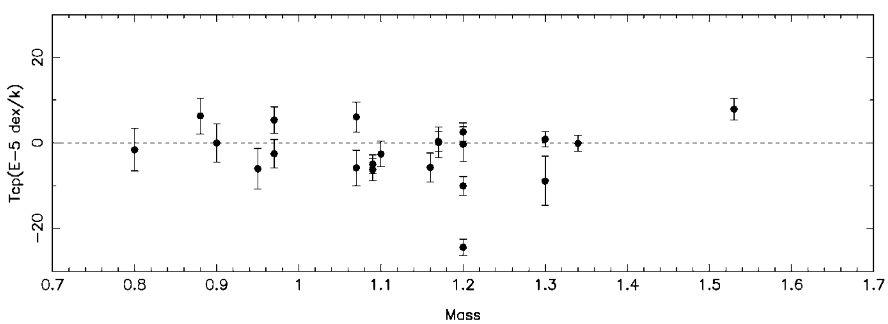

Fig. 2 A plot of sample stars' mass vs. the corresponding T_c slope.

but is not an indication of chemical fractionation. The reason is that oxygen is one of the most volatile elements, and plays a role in calculating the slopes. When [O/Fe] goes down toward higher metallicity, it tends to produce a negative slope in the [X/H] versus T_c plot. Smith et al. (2001) obtained a similar conclusion when they compared their sample planet-harboring stars with field stars.

To investigate the "dynamical" properties of 22 sample stars, we plot the host stars' companion masses (M sin(i)) versus eccentricity (e) and semi-major (a) in the top panels of Figure 5.

Table 1 Metallicity, Mass and Condensation Temperature Slope of 22 Sample Stars

Star	[Fe/H]	Mass ($M_\odot$)	$T_{\rm cp}$ ($\times 10^{-5}$ dex/K)
HD 8574	0.13	1.20	–0.38±4.10
HD 9826	0.15	1.34	–0.14±1.91
HD 10697	0.20	1.17	0.07±3.57
HD 16141	0.07	1.09	–6.25±2.59
HD 20367	0.15	1.16	–5.75±3.34
HD 23596	0.31	1.20	–24.39±1.92
HD 28185	0.26	0.97	–2.56±3.34
HD 33636	0.03	1.10	–2.63±2.99
HD 37124	–0.45	0.80	–1.63±4.96
HD 40979	0.19	1.20	–10.03±2.23
HD 46375	0.19	0.88	6.29±4.21
HD 50554	0.00	1.17	0.31±2.36
HD 52265	0.19	1.20	2.54±2.15
HD 74156	0.11	1.30	0.83±1.83
HD 89744	0.29	0.70	7.88±2.55
HD 106252	–0.04	1.07	6.04±3.51
HD 168443	0.10	1.07	–5.87±4.11
HD 178911	–0.05	1.30	–8.88±5.74
HD 190360	0.19	0.95	–6.07±4.73
HD 195019	0.11	1.09	–5.01±2.15
HD 210277	0.27	0.90	–0.05±4.54
HD 217107	0.40	0.97	5.33±3.10

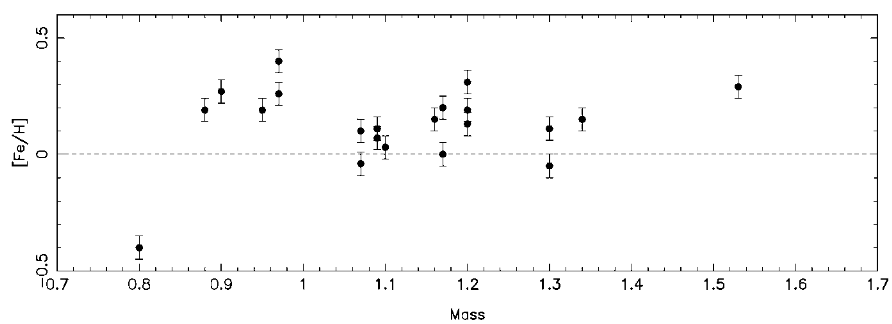

Fig. 3 A plot of sample stars' mass vs. the corresponding [Fe/H], The errors contained systematic errors and the estimated uncertainties of $T_{\rm eff}$, $\log g$ and of the microturbulence, ξ_t. The uncertainties of the stellar parameters are: $\sigma(T_{\rm eff}) = 70\,$K, $\sigma(\log g) = 0.1$ and $\sigma(\xi_t) = 0.3$ km s^{-1}.

In the bottom panel, the eccentricities and semi-major axes are compared. Smith et al. (2001) found a striking difference between the stars with the largest $T_{\rm cp}$ and the others in the distribution of their companion's semi-major axes. In addition, the stars with possible accretion signatures stand out as having smaller orbital separations, as well as smaller eccentricities and companion masses. However, we did not find any significant correlations between those orbital parameters in Figure 5. In the figure, most planet systems have low eccentricities because small

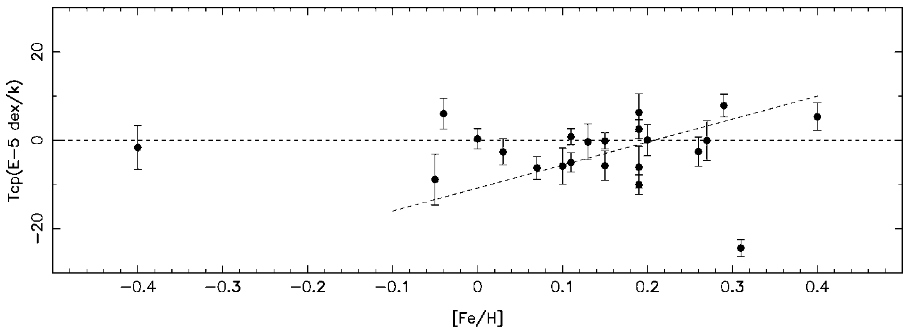

Fig. 4 Derived [X/H] vs. $T_{\rm c}$ slopes are plotted as a function of [Fe/H] for 22 sample stars. The slope of [Fe/H] versus $T_{\rm cp} = 7.3 \pm 9.2 \times 10^{-5}$.

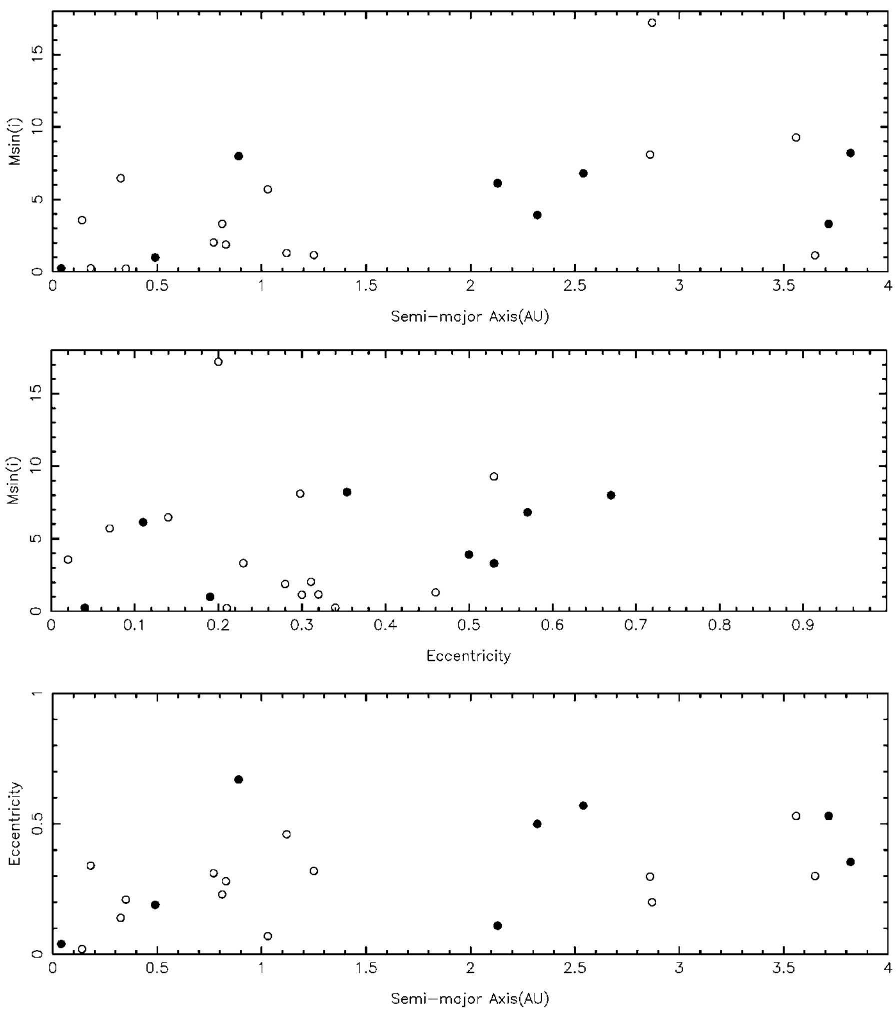

Fig. 5 Orbital properties and masses (Msin(i)) of the planets around stars exhibiting positive [X/H] vs. $T_{\rm c}$ slopes (filled circles) and negative slopes (open circles).

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).

5 CONCLUSIONS

For each of 22 planet-harboring stars, we plotted the abundance of a given element [X/H] against the condensation temperature of that element $T_{\rm c}$, derived the slope of the plot $T_{\rm cp}$, and investigated correlations between the star's mass and metallicity with $T_{\rm cp}$. Consistent with the results presented in Takeda et al. (2001) and Sadakane et al. (2002), we found that no significant correlation between [X/H] and $T_{\rm c}$ can be confirmed in our 22 sample stars, that is , we did not find the obvious signature for the accretion hypotheses. There is no significant trend which will confirm that the parent star had accreted substantial amounts of chemically fractionated material from the proto-planetary disk. The trend in the $T_{\rm cp}$ versus [Fe/H] plot can be interpreted simply as a consequence of ordinary galactic chemical evolution, without supposing any special mechanism related to the formation of planets. Since there is no positive evidence to support the self-enrichment hypothesis, we prefer the hypothesis which says higher primordial metallicity in the star's birth cloud makes it more likely that a star will be accompanied by planets.

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