THE GAS TEMPERATURE IN THE DISSIPATING SOLAR NEBULA: EFFECTS ON THE GAS CAPTURE BY PLANETS.

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Introduction: It is considered that our solar system was formed from the proto-solar nebula. If planets grow to become as massive as the present Mars before the dissipation of nebula gas, they attract the surrounding nebula gas and gain so-called solar-type atmospheres [1, 2]. Mizuno et al. [3, 4] calculated the amounts of rare gases captured by the growing Earth and showed that the proto-Earth captured too much more He and Ne than those exist in the present Earth's atmosphere.

On the other hand, Kominami & Ida [5, 6] showed that the nebula gas whose density is 10^{-4}~10^{-3} times as much as that in the minimum mass solar nebula (MMSN) model is able to damp eccentricities of planets to the present level (order of 0.01) due to its drag force. Although this density of nebula gas is much smaller than that of the MMSN model, it is still large enough for the proto-Earth to capture very large amounts of He and Ne.

In order to resolve this problem, we examine the possibility that the gas temperature in a thin solar nebula is much higher than that of previous estimates. Previous studies adopted the gas density of the MMSN model and assumed that the gas temperature in the solar nebula was 225K near the Earth's orbit [3, 4]. However, at the final stage of planetary formation, the proto-solar nebula gas is dissipating and its density should be lower than that of the MMSN model. In such thin gas, cooling efficiency becomes worse for less frequent collisions among gas particles. Therefore, gas temperature is expected to be much higher than that in the assumption of Mizuno et al. [3, 4]. Increase in the gas temperature results in increase in the thermal energy of nebula gas compared to the gravitational potential of planets. Thus, it results in order of magnitude decrease of the amount of nebula gas (i.e., He and Ne) captured by the proto-Earth (Fig. 1).

In this study, we calculate the temperature of the solar nebula gas whose density is 10^{-4} times as much as that in the MMSN model, and examine the possibility that the problem of rare gas abundances and eccentricity damping due to nebula gas are reconciled.

Model: In our calculations, surface density of nebula gas $\Sigma_{\rm gas}$ is given by

$$\Sigma_{\rm gas} = 10^{-4}\,\Sigma_{\rm gas}^{\rm min} = 0.17\left(r/{\rm AU}\right)^{-3/2} \quad [{\rm g\ cm^{-2}}], \qquad (1)$$

where $\Sigma_{\rm gas}^{\rm min}$ is the surface density assumed in the MMSN model. The vertical structure of nebula gas is derived by the assumption of hydrostatic equilibrium of isothermal gas. Then the number density of nebula gas is given by

$$n_{\rm gas}(r,z) = 6.14\times10^{10}\left(\frac{T_{\rm gas}}{282\,[{\rm K}]}\right)^{-1/2}\left(\frac{r}{1\,[{\rm AU}]}\right)^{-3} \times\exp\left(-\frac{z^2}{H^2}\right) \quad [{\rm cm^{-3}}], \qquad (2)$$

where $T_{\rm gas}$ and H are temperature and scale height of nebula gas, respectively. We ignore the effect of possible vertical temperature variations on the density structure.

Gas temperature is calculated by the following equation:

$$\rho_{\rm gas} C_v \frac{\partial T_{\rm gas}}{\partial t} = \Gamma_{\rm PE} + \Gamma_{\rm CR} + \Gamma_{\rm Xray} - \Lambda_{\rm CO} - \Lambda_{\rm OI} - \Lambda_{\rm gg} \qquad (3)$$

where $\rho_{\rm gas}$ and C_v are the mass density and specific heat of nebula gas. Terms in the right hand side of the above equation represent heating and cooling rates. Heating rates due to the photoelectric effect, solar X-

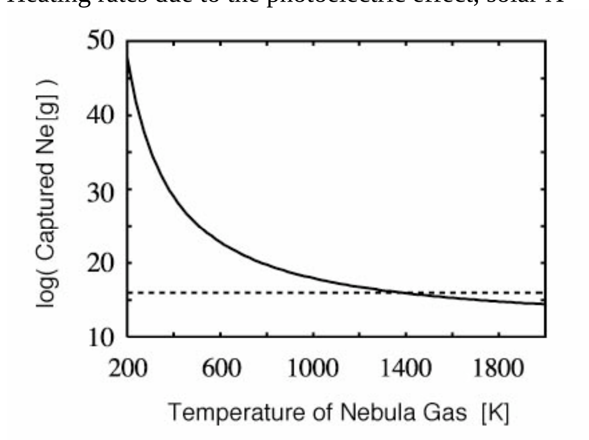

Figure 1. The amount of Ne captured by an Earth-sized planet from the surrounding isothermal nebula gas, whose density is 10^{-4} times as much as that in the MMSN model (a solid line). It is shown that if the temperature of the nebula gas rises to about 1400K, the amount of Ne decreases to that contained in the present Earth's atmosphere (a dashed line).

ray and cosmic ray ionization are included. Cooling processes due to the rotational lines of CO and the metastable line of OI are included. Thermal coupling between gas and dust particles is also taken into ac count.

Density distribution of dust particles are derived from the assumption that the mass density of dust particles $\rho_{\mathrm{dust}}(r,z)$ is proportional to that of gas $\rho_{\mathrm{gas}}(r,z)$. Therefore, dust-to-gas mass ratio δ_{dg} is assumed to be constant at every point in the disk. Size and material density of dust particles are assumed to be $a = 3\,\mu\mathrm{m}$ and $\rho_{\mathrm{dust}} = 3\,\mathrm{g/cm^3}$ (silicate).

For the initial condition, complete coupling of dust and gas temperature, i.e., $T_{\mathrm{gas}} = T_{\mathrm{dust}}$ is assumed. Dust temperature T_{dust} is derived from the assumption of spherical black body:

$$T_{\mathrm{dust}} = 282.5\,\left(L_*/L_{\mathrm{Sun}}\right)^{1/5}\left(r/\mathrm{AU}\right)^{-2/5}\left(a/\mu\mathrm{m}\right)^{-1/5} \quad (5)$$

where L_* and L_{Sun} are luminosities of the central star and the present Sun, respectively.

Results and Discussion: It was found that the gas temperature is strongly dependent on the abundances of CO and dust particles, which are effective coolants of nebula gas. We calculated the gas temperature at a heliocentric distance of 1AU with various values of the fraction of CO in the nebula gas, $n_{\mathrm{CO}}/n_{\mathrm{gas}} = 10^{-6} \sim 10^{-4}$, and dust-to-gas mass ratio, $\delta_{\mathrm{dg}} = 10^{-6} \sim 10^{-2}$. It is shown that in case both $n_{\mathrm{CO}}/n_{\mathrm{gas}}$ and δ_{dg} are lower than 10^{-6}, gas temperature exceed 10^3 K even at the disk midplane (Fig. 2).

As the possible process to decrease the abundance of CO in the dissipating solar nebula, we consider the effect of photodissociation. Indeed, the gas density of 10^{-4} times as much as that in the MMSN model is not small enough for UV radiation to penetrate close to the midplane of disk. However, we have found that if vertical mixing in nebula gas is taken into account, order of decrese in CO near the midplane of disk can occur due to the photodissociation in the surface region of nebula gas. Effects of other reactions that can reproduce CO should be investigated henceforth.

Dust abundance at the final stage of planetary formation is, probably, more uncertain parameter. Since dust particles are consumed through the process of planetary formation, it is likely that the abundance of small dust particles at this stage becomes lower than that in the "proto-" planetary disk. However, it is also possible that small dust particles are again produced through collisions and fragmentations of remnant planetesimals. In order to examine effects on the gas temperature, it is necessary to investigate the effect of radiation pressure and Poynting-Robertson effect, which are dependent on the size of dust particles and have influence on the timescale during which they are able to exist in the nebula gas.

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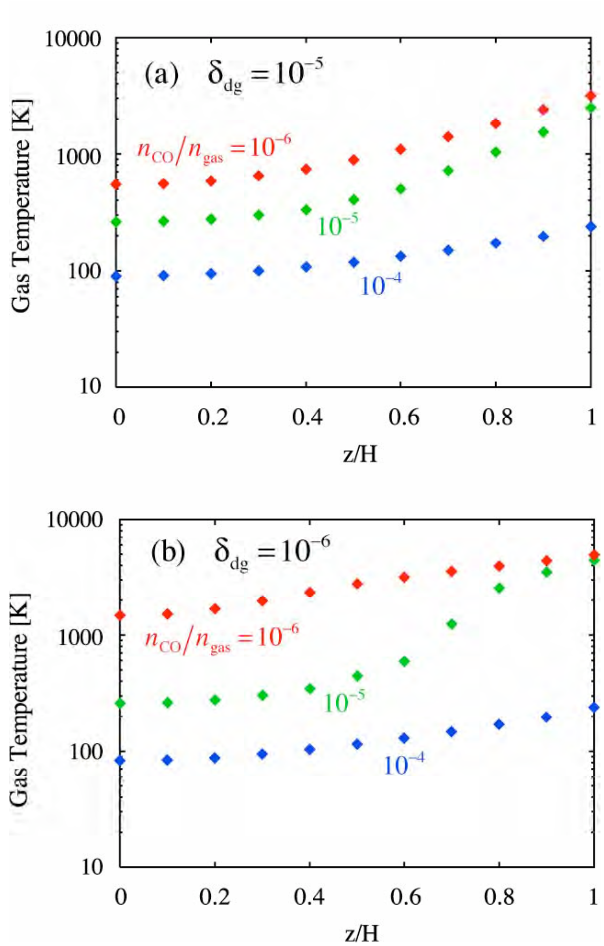

Figure 2. The gas temperature as a function of z, normalized with the disk scale height H at a radial position of 1AU with (a) $\delta_{\mathrm{dg}} = 10^{-5}$ and (b) $\delta_{\mathrm{dg}} = 10^{-6}$. Results with the three different fractions of CO in the nebula gas, i.e., $n_{\mathrm{CO}}/n_{\mathrm{gas}} = 10^{-6}$ (red points), 10^{-5} (green points) and 10^{-4} (blue points) are shown.