Hydrodynamic Escape of Planetary Atmospheres

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1. Introduction

How and from what sources the atmospheres of Earth, Mars and Venus formed, and how they evolved to their present states, are classic problems in the planetary sciences. Carbon dioxide is the principal species on Mars and Venus; on Earth, it's nitrogen. One might expect that these "sister" planets, not very different in mass or distance from the sun, would have acquired similar primordial atmospheres in their youth and followed similar evolutionary paths to the present.

Hydrodynamic escape is one of a few mechanisms that can change the composition of a planetary atmosphere irreversibly (e.g. Hunten, 1990). So far, several numerical models have been developed previously to solve the hydrodynamic escape problem (Watson et al., 1981; Kasting & Pollack, 1983; Tian et al., 2005). Their models, however, is unsatisfactory to apply actual atmospheric evolution because they cannot solve transonic solutions or multi component solutions. Here we present the first study on the multi component time-dependent hydrodynamic equations for transonic neutral gas escape from planetary atmospheres. We then apply it to the escape of hypothetical early Venusian atmosphere.

2. Numerical Model

The one-dimensional time-dependent nonviscous hydrodynamic equations for a two-component atmosphere in spherical geometry are written

$$\frac{\partial n}{\partial t} + u\frac{\partial n}{\partial r} = -n\frac{\partial u}{\partial r} - \frac{2nu}{r}$$

$$\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial r}$$
$$= -\frac{1}{nm}\frac{\partial p}{\partial r} - \frac{GM}{r^2} + (u_i - u)nk_i - \frac{\alpha_T k}{m}\left(\frac{n_i}{n_i + n}\right)\frac{\partial T}{\partial r}$$

$$\frac{\partial p}{\partial t} + u\frac{\partial p}{\partial r} = -\gamma p\frac{\partial u}{\partial r} - \frac{2\gamma pu}{r} + (\gamma - 1)q.$$

The number density, bulk radial velocity, mass, pressure, and temperature are represented by n, u, m, p, and T, respectively; the corresponding quantities for the other component are labeled with the subscript “i.” In the momentum equation, the effects of collisions with the other species are included in the last two terms. The first of these accounts for the transfer of momentum from one mean flow to the other; the parameter k_i stands for the momentum transfer collision rate. The last term accounts for thermal diffusion; α_T is the thermal diffusion factor. These parameters are given by experimental data (Zahnle & Kasting, 1986). We assumed that heating by solar EUV radiation q occurred in a single layer which is given in the bottom of the atmosphere. Compelling observational evidence shows that the solar EUV flux was 10-100 times larger than the present value about 4.5Gy ago (Ribas et al., 2005). So we use some q value as a parameter.

The Constrained Interpolation Profile (CIP) method is used to solve the system. CIP method can solve the subsonic-transonic-sonic conditions smoothly (Yabe et al., 2001).

3. Applications to the Early Venusian Atmosphere

3.1 Loss of Water from Venus

Donahue et al. (1982) reported a D/H ratio in the Venus clouds of $(1.6 \pm 0.2) \times 10^{-2}$, or about 100 times higher than the terrestrial value. If Venus and Earth had similar D/H ratios initially, this implies that Venus must have started out with at least 100 times as much water as is now present. Venus is free of oxygen but it is thought to have contained a primordial water ocean, giving rise to a dense steam atmosphere and a subsequent strong greenhouse effect. The present lack of water is supposed to be due to photodissociation of H_2O followed by thermal escape of H at early stage. A possible problem for such models is the question of how to dispose of the oxygen presumed to have been left behind after the hydrogen had escaped. One hypothesis is the loss of oxygen by oxidation of the crust, but it was shown by Lewis and Prinn (1984) that the trapping of about 100 bars of O_2 over geological times should impose a permanent extrusion of nonoxidized material with a rate much larger than on Earth, which seems implausible.

An alternative explanation which has apparently been overlooked is that oxygen escape to space along with hydrogen. Watson et al. (1981) found that XUV-driven energy-limited hydrodynamic conditions would have resulted in the upper limit of the hydrogen escape flux of about 10^{12} /cm^{2}s, which would evacuate the amount of a terrestrial water ocean in about 280 My. On the other hand, Kasting & Pollack (1983) showed that the escape flux is approximately four times lower than the energy-limited flux calculated by Watson et al., because it is source limited at the base of the expansion. Then Zahnle & Kasting (1986) concluded that substantial quantities of water may have been lost without the need to oxidize large amounts of the crust. So far, we have not validated the idea assuredly. To pursue this idea in an accurate quantitative fashion, we must examine in detail the processes by which hydrogen has escape to space by time-marching numerical study. In this study, our 2-type numerical models applied to the escape of hydrogen and oxygen from the early Venus to examine the effect of hydrogen-oxygen drag.

3.2 Fractionation of Noble Gasses on Venus

Free from the entanglements of chemical interactions, compositions of noble gasses are clues to the characteristics of their source reservoirs, and are ideal recorders of mass fractionations imprinted by physical processing such as escape from planetary gravitational fields. Information of noble gasses abundances for Venus comes from atmospheric measurements by mass spectrometers on the Venera and Pioneer Venus spacecraft (Wieler, 2002). Venus may have lost some Ne, since it is enriched about 10% in ^{22}Ne/^{20}Ne with respect to solar abundances. On the other hand, Venus appears to have lost no Ar, as indicated by near solar ^{36}Ar/^{84}Kr and ^{38}Ar/^{36}Ar ratios (Fig. 1 after Pepin, 2006).

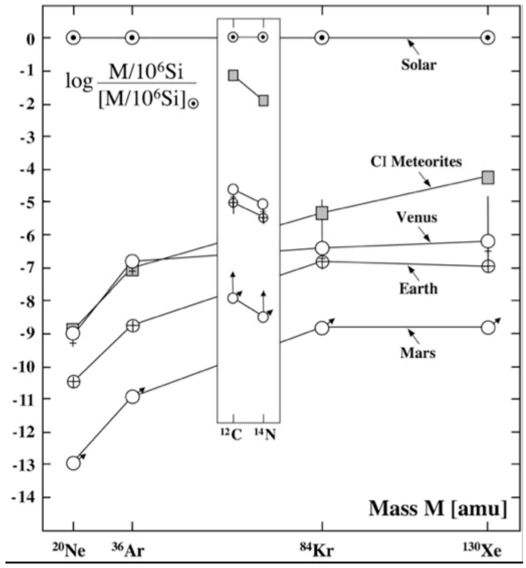

Figure 1. Abundances of noble gases in terrestrial planet atmospheres and in primitive meteorites, represented relative to solar abundances in units of atoms per 10^6 Si atoms (Pepin, 2006).

Noble gas depletion patterns were probably created from initially solar compositions by different processes acting in atmospheres and meteorites, on planets by gravitational escape and outgassing, and in the meteorites by mass-dependent adsorption mechanisms. Gravitational escape of atmospheric constituents is intrinsically mass-dependent, no matter the specific loss mechanism, and so both elements and isotopes in the residual atmospheres are fractionated with respect to initial compositions. Noble gases on Mars, Earth and Venus carry powerful evidence that their primordial parents had solar compositions, and that gravitational escape played a major role in their evolution. Analytical approximations to mass fractionation during hydrodynamic escape indicated that these fractionation could be achieved in some instances for the case of a heavy constituent being dragged along by a much lighter one (Zahnle & Kasting, 1986). In this study, our numerical model applied to the escape of noble gases in hydrogen escaping flow from the early Venus to examine whether the fractionation can be achieved or not.

4. Results & Discussions

Figure 1 shows velocity distributions of hydrogen and oxygen in two different cases. The solid curve in Fig. 1., we calculated the rate at which trace heavy gases are carried to space by a vigorous hydrogen wind. The pointed curve in Fig. 1., the calculations are extended to atmospheres in which hydrogen and oxygen are same amount. The velocity of H_2 decreases to a large degree as well as that of O in latter case. Because of that, oxygen would be lost much less than in former case. It shows that to dispose the whole oxygen by hydrodynamic escape would be difficult if hydrogen and oxygen are same amount. In order to estimate how much oxygen would be left behind after the hydrogen escape precisely, we should consider interactions between H_2 and O in more realistic model. And also we should take solar EUV evolution into account to study the evolution of Venusian atmosphere.

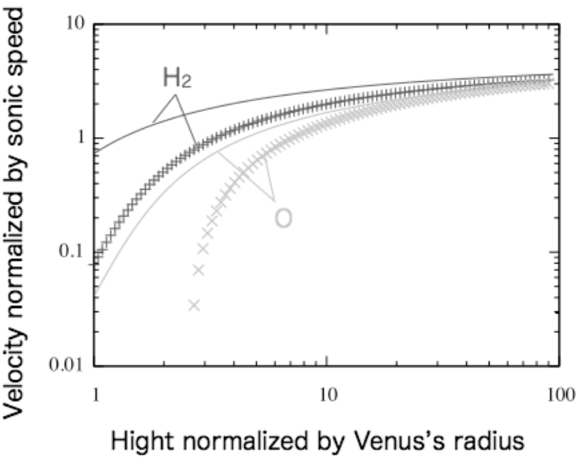

Figure 1. Velocity distributions in the steady state of hydrodynamic escape of hydrogen and oxygen from Venus. The solid lines show the escape velocity in case of $H_2 \gg O$. The pointed lines show the escape velocity in case of $H_2 \fallingdotseq O$.

In Fig. 2, we have indicated the points at which noble gases would have begun to escape. The fractionation of noble gases, especially Ne and Ar, might not be explained within the framework of hydrodynamic escape, unless the solar EUV value was fine adjusted. This circumstance would not be realistic. So we should consider a photochemical reaction as follow.

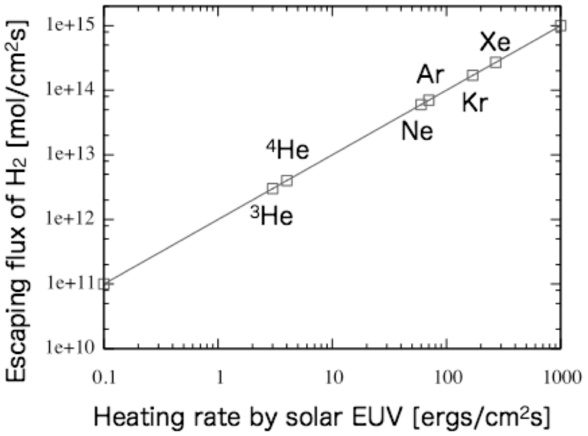

Figure 2. Illustration of hydrodynamic escape of atmospheres from Venus. The escape fluxes at which the various noble gases would begin to escape are indicated.

Any wind capable of lifting Ne is also capable of lifting CO. At the top of the atmosphere, infrared cooling by CO might then have radiated away EUV energy that would otherwise speed the flow. In other words, the wind may only have become strong enough to reach the threshold of removing CO, at which point any additional EUV energy input would be radiated away. It would therefore be expected that some loss of Ne occurred, but that no loss of the heavier Ar took place. The fractionation of the Venus' noble gases might be explained by this mechanism.

5. Future Works & Hopes

The calculated value of the hydrodynamic escape flux depends upon the hydrogen number density in the lower thermosphere which, in turn, is controlled by a combination of chemical, diffusive, and advective processes. Heating and cooling rates, heat capacities, and thermal conductivities are also functions of atmospheric composition. And if a planetary atmosphere like that of Venus is not protected by a strong intrinsic magnetic field, the planetary neutral gas in the exosphere can be ionized due to charge exchange with the deflecting solar wind plasma flow, by electron impact and by the XUV radiation, and picked up by the solar wind plasma flow around the planet (Shizgal & Arkos, 1996). Our numerical model should be improved to be more realistic.

By the way, Venus is the least documented of the three planets. The questions of Venusian atmosphere may be answered someday by performing chemical analysis to determine the oxidation state of Venus' crust or a modern flight spectrometer sampling the Venusian atmosphere could answer many of the most central questions.

Acknowledgments

We thank H. Genda for thoughtful comments on coding the numerical model. This study was completed under the support of a JSPS Research Fellowship.

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