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Runaway Greenhouse Atmospheres: Applications to Earth and Venus

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ABSTRACT

Runaway greenhouse atmospheres are discussed from a theoretical standpoint and with respect to various practical situations in which they might occur. The critical solar flux required to trigger a runaway greenhouse is at least 1.4 times the solar flux at Earth's orbit (S_o). Rapid water loss may occur, however, at as little as 1.1 S_o, from a type of atmosphere termed a "moist greenhouse." The moist greenhouse model provides the best explanation for loss of water from Venus, if Venus did indeed start out with a large amount of water. The present enrichment in the D/H ratio on Venus provides no unambiguous answer as to whether or not it did. A runaway greenhouse (or "steam") atmosphere may have been present on the Earth during much of the accretion process. Evidence from neon isotopes supports this hypothesis and provides some indication for how long a steam atmosphere may have lasted. Finally, the theory of runaway and moist greenhouse atmospheres can be used to estimate the position of the inner edge of the continuously habitable zone around the Sun. Current models place this limit at about 0.95 AU, in agreement with earlier predictions.

INTRODUCTION

The topic of runaway greenhouse atmospheres has received renewed attention over the past several years for three different reasons. The first concerns the history of water on Venus. Although there is still no concensus as to whether Venus had much water to begin with (Grinspoon 1987;

Grinspoon and Lewis 1988), some recent theories of accretion (Wetherill 1985) predict extensive radial mixing of planetesimals within the inner solar system. If this idea is correct, then Venus must initially have received a substantial fraction of Earth's water endowment. This water is obviously not present on Venus today. The mixing ratio of water vapor in the lower atmosphere of Venus is approximately 10^{-4}; thus, the total amount of water present is only about 10^{-5} times the amount in Earth's oceans. The runaway greenhouse theory provides a convenient explanation for how the rest of Venus' water might have been lost.

A runaway greenhouse atmosphere may also have been present on Earth during at least part of the accretionary period. Matsui and Abe (1986a,b) and Zahnle *et al.* (1988) have shown that an impact-induced steam atmosphere could have raised the Earth's surface temperature to 1500 K, near the solidus temperature for typical silicate rocks. This implies the existence of a global magma ocean of unspecified depth. Although the continuous existence of such a steam atmosphere has been questioned (Stevenson 1987), an analysis of terrestrial neon isotope data (Kasting 1990) strongly supports the notion that such an atmosphere existed during some portion of the accretionary period.

A third reason for interest in runaway greenhouse atmospheres concerns their implications for the existence of habitable planets around other stars. Any planet that loses its water as a consequence of a runaway greenhouse effect is not likely to be able to support life as we know it. Thus, the idea that runaway greenhouses are possible sets limits on the width of the continuously habitable zone (CHZ) around our Sun and around other main sequence stars (Hart 1978, 1979; Kasting and Toon 1989). One of the most important reasons for studying runaway greenhouses is to try to estimate the chances of finding another Earth-like planet elsewhere in our galaxy.

Here, the theory of runaway greenhouse atmospheres is briefly reviewed, and the consequences for the three problems mentioned above are discussed.

RUNAWAY GREENHOUSE ATMOSPHERES

The concept of the runaway greenhouse atmosphere was introduced by Hoyle (1955) and has been further developed by Sagan (1960), Gold (1964), Dayhoff *et al.* (1967), Ingersoll (1969), Rasool and DeBergh (1970), Pollack (1971), Goody and Walker (1972), Walker (1975), Watson *et al.* (1984), Matsui and Abe (1986a,b), Kasting (1988), and Abe and Matsui (1988). The basic idea, as explained by Ingersoll (1969), is that there exists a critical value of the solar flux incident at the top of a planet's atmosphere above which liquid water cannot exist at the planet's surface. Intuitively, one expects this to be the case. If Earth were by some means to be pushed closer and closer to the Sun, one would anticipate that at some point the oceans would be vaporized and the planet would be enveloped in a dense, steam atmosphere. The amount of water in Earth's oceans, 1.4×10^{24} g, is such that the surface pressure of this atmosphere would be about 270 bar. For comparison, this is ~50 bar greater than the pressure at the critical point of water (647.1 K, 220.6 bar).

It should be noted that the term "runaway greenhouse" has also been used to describe the positive feedback between the surface temperature of a planet and the amount of water vapor in its atmosphere. An increase in surface temperature causes an increase in the vapor pressure of water which, in turn, leads to an enhanced greenhouse effect and a further increase in surface temperature. Although this type of positive feedback certainly exists, there is no reason to believe that Earth's present climate system is unstable. Surface temperature is simply a monotonically increasing function of the incident solar flux. Thus, the phrase "runaway greenhouse" is best reserved to describe a situation in which a planet's surface is entirely devoid of liquid water.

The single most important characteristic of a runaway greenhouse atmosphere is the critical solar flux required to trigger it. Only recently have detailed estimates of this energy threshold been made (Kasting 1988; Abe and Matsui 1988). Even these estimates, which were obtained using elaborate radiative-convective climate models, cannot be considered reliable. The greatest uncertainty in performing such a calculation is the effect of clouds on the planetary radiation budget. Kasting (1988) has derived results for a fully saturated, cloud-free atmosphere. (Actually, clouds were crudely parameterized in this model by assuming an enhanced surface albedo.) The critical solar flux in his model is 1.4 S_o, where S_o is the present solar flux at Earth's orbit (1360 W m^{-2}). An Earth-like planet with Earth-like oceans was assumed. Abe and Matsui (1988) have performed a similar calculation for a case in which part of the energy required to trigger the runaway greenhouse was derived from infalling planetesimals. (Their study was specifically directed at the problem of atmospheric evolution during the accretion period.) The amount of accretionary heating required to trigger runaway conditions in their model, 150 W m^{-2}, is the same as the value derived by Kasting (1988) for an analogous simulation. (See his Figure 13.) Thus, the two existing detailed calculations of the energy threshold of the runaway greenhouse are in good agreement.

Although clouds cannot reliably be parameterized in such an atmosphere, their qualitative effect on the planetary radiation balance is not difficult to determine (Kasting 1988). An atmosphere rich in water vapor would probably exhibit at least as much fractional cloud cover as the current

Earth and possibly much more. Although clouds affect both the incoming solar and outgoing infrared radiation, the solar effect should dominate because a water vapor atmosphere would already be optically thick throughout the infrared. Thus, the main effect of increased cloud cover should be to reflect a greater proportion of the incident solar radiation, thereby diminishing the amount of energy available to sustain a steam atmosphere. It follows that the energy threshold for a runaway greenhouse is almost certainly higher than 1.4 S_o. How much higher is uncertain, but values as high as 5 S_o are within the realm of possibility (Kasting 1988, Figure 8c).

These rather speculative theoretical models should be weighed against an observational fact: our neighboring planet Venus has very little water in its atmosphere, less than 200 ppm by volume (Moroz 1983; von Zahn *et al.* 1983). As discussed further below, it is not clear whether this lack of water is innate to the planet or whether it is the result of an evolutionary process. One possibility, however, is that Venus was initially water-rich, and that it lost its water by photodissociation in the upper atmosphere followed by escape of hydrogen. (See references in opening paragraph.) If this theory is correct, then Venus must have experienced either a runaway greenhouse or a phenomenon akin to a runaway greenhouse at some time in the past. The solar flux at Venus' orbit is currently 1.91 S_o. Based on stellar evolution models, the Sun's output was some 25-30% lower (1.34-1.43 S_o) early in solar system history (Gough 1981). This implies that the critical threshold for losing water from a planet is no higher than 1.9 S_o and may well be considerably lower.

If this was all there was to the problem, one could reliably conclude that the energy threshold for the runaway greenhouse was between 1.4 S_o and 1.9 S_o. However, it has recently been demonstrated that there are other ways for a planet to lose water rapidly besides the runaway greenhouse. An alternative possibility, proposed by Kasting *et al.* (1984) and Kasting (1988) is that Venus experienced a so-called "moist greenhouse," in which the planet lost its water while at the same time maintaining liquid oceans at its surface. This turns out to be slightly favored from a theoretical standpoint; it also requires a significantly lower energy input than does the runaway greenhouse model. This alternative theory is described briefly below.

MOIST GREENHOUSE ATMOSPHERES

The concept of the moist greenhouse atmosphere stems from the analysis of moist adiabats by Ingersoll (1969). Ingersoll showed that the vertical distribution of water vapor in an atmosphere should be strongly correlated with its mass-mixing ratio $c_o(H_2O)$ near the surface. When water vapor is a minor constituent of the lower atmosphere [$c_o(H_2O) < 0.1$], its concentration declines rapidly with altitude throughout the convective region as a consequence of condensation and rainout. This is the situation in Earth's atmosphere today, where $C_o(H_2O)$ declines from roughly 0.01 near the surface to about 3×10^{-6} in the lower stratosphere. When water vapor is a major constituent [$c_o(H_2O) > 0.1$], however, its behavior is quite different. The amount of latent heat released by condensation becomes so large that the temperature decreases very slowly with altitude, and the water vapor mixing ratio remains nearly constant. This allows water vapor to remain a major constituent even at high altitudes which, in turn, allows it to be effectively photodissociated and the hydrogen lost to space. (The important constraint here is that water vapor remain abundant above the cold trap, i.e. the maximum height at which it can condense. When this criterion is satisfied, hydrogen should escape at close to the diffusion-limited rate (Hunten 1973), as long as sufficient solar extreme ultraviolet (EUV) energy is available to power the escape.)

Kasting *et al.* (1984) and Kasting (1988) have applied the moist greenhouse model to the problem of water loss from an Earth-like planet. The most recent results (Kasting 1988) indicate that hydrogen escape becomes very rapid (i.e. $c_o(H_2O)$ becomes greater than 0.1) for incident solar fluxes exceeding 1.1 S_o. As before, this calculation was performed for a fully saturated, cloud-free atmosphere, so the actual value of the solar flux at which water loss becomes efficient is probably greater than this value. The calculation does demonstrate, however, that Venus could have lost most of its water without ever experiencing a true runaway greenhouse. Indeed, the solar flux at Venus's orbit early in solar system history (1.34 – 1.43 S_o) is so close to the minimum value required for runaway (1.4 S_o) that it seems likely that clouds would have tipped the balance in favor of the moist greenhouse scenario. Thus, if Venus were originally endowed with as much water as Earth, it may at one time have had oceans at its surface.

With the concepts of runaway and moist greenhouses in mind, let us now return to the three topics mentioned in the introduction.

LOSS OF WATER FROM VENUS

The real issue concerning Venus is not so much whether it could have lost its water but, rather, whether it had any appreciable amount of water initially. It is now well accepted that the D/H ratio on Venus is very high: approximately 100 times the terrestrial value. The original interpretation of this observation (Donahue *et al.* 1982) was that Venus was once wet. If Venus and Earth started out with similar D/H ratios, which seems even more likely now in view of the terrestrial D/H ratio observed in the tail of comet Halley (Eberhardt *et al.* 1987), this measurement implies that Venus once had at least 100 times as much water as it does now. The current water abundance on Venus, assuming a lower atmosphere mixing ratio of 100 ppmv, is only 0.0014% of a terrestrial ocean. Thus, this minimal interpretation requires only that Venus start out with about 0.1% of Earth's water endowment. Even advocates of a dry early Venus would probably not dispute such a claim, given the potential for radial mixing of planetesimals during the accretion process (Wetherill 1985). If, however, some deuterium was lost along with the escaping hydrogen (which seems, indeed, to be unavoidable), the amount of water that was lost could be orders of magnitude greater. Consequently, proponents of a wet origin for Venus (Donahue *et al.* 1982; Kasting and Pollack 1983) have suggested that Venus may well have started out with an Earth-like water endowment.

The wet-Venus model has been challenged by Grinspoon (1987) and Grinspoon and Lewis (1988), who point out that the present D/H enrichment on Venus could be explained if the water abundance in Venus' atmosphere were in steady state. Loss of water by photodissociation and hydrogen escape could be balanced by a continued influx of water from comets. Grinspoon and Lewis's steady-state model has, in turn, been criticized (Donahue, private communication, 1988) on the grounds that they underestimated the amount of water vapor in Venus' lower atmosphere. The time constant for evolution of the D/H ratio in Venus' atmosphere can be expressed as (Grinspoon 1987)

$$\tau \sim R/(f\phi) \tag{1}$$

where R is the vertical column abundance of water vapor in the atmosphere, ϕ is the hydrogen escape rate, and f is the D/H fractionation factor (i.e. the relative efficiency of D escape compared to H escape). Best estimates for the values of ϕ and f, based on a weighted average of the hydrogen loss rates from charge exchange with H^+ and from momentum transfer with hot O atoms, are 2×10^7 H atoms cm^{-2} s^{-1} and 0.013, respectively (Hunten *et al.* 1989). This estimate draws upon a reanalysis of the charge exchange process by Krasnopolsky (1985). Grinspoon (1987) assumed that the Venus lower atmosphere contained only 20 ppmv of water vapor; this gives $R \approx 6 \times 10^{22}$ H atoms cm^{-2} and $\tau \approx 7 \times 10^9$ years. Even this value is somewhat longer than the age of the solar system, indicating that the steady-state model is marginally capable of explaining the observations. Small increases in the value of either ϕ or f could eliminate the time scale problem. If the H_2O mixing ratio is actually closer to 200 ppm, however, then $\tau \approx 7 \times 10^{10}$ years, and the steady-state model is in serious trouble.

Resolution of this question requires, at a bare minimum, that the present controversy regarding the H_2O content of the Venus lower atmosphere be resolved. Our present understanding of Venus' water inventory is further muddled by the fact that the H_2O mixing ratio apparently varies with altitude from about 20 ppmv near the surface to 200 ppmv just below the clouds (von Zahn *et al.* 1983). Until this variation is explained theoretically, little confidence can be given to any of the measurements, and the H_2O abundance on Venus will remain an enigma.

Setting aside the problem of the initial water endowment, subsequent aspects of the evolution of Venus' atmosphere are now reasonably well understood (Kasting and Toon, 1989). If Venus had water originally, most of it was lost through either the runaway or moist greenhouse processes described above. One additional reason for favoring the moist greenhouse model is that it might have facilitated removal of the last few bars of Venus' water (Kasting *et al.*, 1984). If an ocean had been present on Venus for any significant length of time, it should have drawn down the atmospheric CO_2 partial pressure by providing a medium for the formation of carbonate minerals. A thinner atmosphere would, in turn, have provided less of a barrier to loss of water by photodissociation followed by hydrogen escape. For example, suppose that an initial 100-bar CO_2-N_2 atmosphere was reduced to 10 bar of total pressure by carbonate formation. The critical water abundance at which the cold trap became effective would then be reduced from 10 bar to 1 bar, based on the criterion $c_o(H_2O) < 0.1$. Only 1 bar of water would then need to be lost by the relatively inefficient hydrogen loss processes that would have operated after the cold trap had formed.

Once surface water was depleted, carbonate formation would have slowed dramatically, and CO_2 released from volcanos should have begun accumulating in the atmosphere. SO_2 concentrations would have likewise increased, and the modern sulfuric acid clouds would have started to form. Thus, regardless of its initial condition, Venus' atmosphere should eventually have approached its modern state.

STEAM ATMOSPHERES DURING ACCRETION

The possibility that Earth was enveloped in a dense steam atmosphere during the accretionary period was raised by Matsui and Abe (1986a,b, and earlier references therein). Their model elaborated on earlier studies (Benlow and Meadows 1977; Lange and Ahrens 1982) that predicted that infalling planetesimals would be devolatilized on impact once the growing Earth had reached about 30% of its present radius. The water contained in these impactors would thus have been emplaced directly into the protoatmosphere, instead of following the more traditional route of being first incorporated into the solid planet and being subsequently outgassed from volcanos.

A critical aspect of Matsui and Abe's model was that it considered the effect of the impact-induced steam atmosphere on the planetary radiation budget. Based on a relatively crude, grey-atmosphere, radiative-equilibrium calculation, they argued that the surface temperature of such an atmosphere would rise to the approximate solidus temperature of crustal rocks, about 1500 K. The surface pressure would continue to rise until it was of the order of 100 bar. At this point dissolution of water in the partially molten planetary surface would balance the continued input of water from planetesimals and thereby stabilize the atmospheric pressure and temperature.

Matsui and Abe's fundamental predictions have been largely borne out by studies carried out using more detailed models (Kasting 1988; Zahnle *et al.* 1988; Abe and Matsui 1988). Given an accretionary time scale of 10^7 to 10^8 years (Safronov 1969), the rate of energy release from infalling material should indeed have been sufficient to maintain the atmosphere in a runaway greenhouse state (Kasting 1988, Figure 13). One objection that has been raised, however, is that none of these models have taken into account the stochastic nature of the accretion process (Stevenson 1987). If the latter stages of accretion were dominated by large impacts spaced at relatively long time intervals (Wetherill 1985), a steam atmosphere may have existed only for short time periods following these events.

Some light can be shed on this otherwise difficult question by an analysis of neon isotopic data. Craig and Lupton (1976) pointed out some time ago that the $^{20}Ne/^{22}Ne$ ratio in Earth's atmosphere (9.8) is lower than that in gases thought to originate in the mantle. Their database has now been expanded to include volcanic gases, along with trapped gases in diamonds and MORBs (mid-ocean ridge basalts) (Ozima and Igarashi 1989). The neon isotope ratio in gases derived from the mantle is generally between 11 and 14, with the lower values attributed to mixing with atmospheric neon (Ozima and Igarashi 1989). Thus, the $^{20}Ne/^{22}Ne$ ratio of mantle neon is similar to the solar ratio, which ranges from 13.7 in the solar wind to 11-12 in solar flares (Ozima and Igarashi 1989).

The neon isotopic data are most easily explained if Earth formed from material with an initially solar $^{20}Ne/^{22}Ne$ ratio, and if ^{20}Ne was preferentially lost from Earth's atmosphere during rapid, hydrodynamic escape of hydrogen (Kasting 1990). The requirements for losing neon are quite specific and can be used to set rather tight constraints on the composition of Earth's atmosphere at the time when the escape occurred. The minimum hydrogen escape flux required to carry off ^{20}Ne is 2×10^{13} H_2 mol cm^{-2} s^{-1} (Kasting 1989). If the background atmosphere at high altitudes was predominantly CO_2, the diffusion-limited escape rate of hydrogen is given by

$$\phi_{lim} \approx 3 \times 10^{13}\, f(H_2)/[1 + f(H_2)] cm^{-2} s^{-1} \qquad (2)$$

where $f(H_2)$ is the atmospheric H_2 mixing ratio (Hunten 1973). By comparing this expression with the escape rate needed to carry off neon, one can see that this is only possible if $f(H_2)$ exceeds unity, i.e. the atmosphere must be composed primarily of hydrogen. Such an atmospheric composition would have been very difficult to sustain during most of Earth's history. However, it is entirely reasonable in an impact-induced steam atmosphere, where copious amounts of H_2 could have been generated from the reaction of H_2O with metallic iron.

A second reason that the escape of neon must have occurred early is that this is the most favorable period from an energetic standpoint. The solar EUV energy flux required to power an escape rate of 2×10^{13} H_2 mol cm^{-2} s^{-1} is about 40 ergs cm^{-2} s^{-1}, or roughly 130 times greater than the present solar minimum EUV flux (Kasting 1989). EUV fluxes of this magnitude are expected only within the first 10 million years of solar system history (Zahnle and Walker 1982). Thus, the isotopic fractionation of neon must have taken place during the accretionary period, most likely in a steam atmosphere of impact-induced origin.

If this explanation for the origin of the atmospheric $^{20}Ne/^{22}Ne$ ratio is correct, it is possible to use this information to estimate the length of time that a steam atmosphere must have been present on the growing Earth. According to theory (Zahnle *et al.* 1988), the surface pressure of the steam atmosphere should have been buffered at a more or less constant value of $\sim$ 30 bar. Application of the "constant inventory" model for hydrodynamic mass fractionation (Hunten *et al.* 1987) then predicts that the escape episode must have lasted at least five million years (Kasting 1989). Thus, even if large impacts were important and steam atmospheres were essentially a transient phenomenon, the neon isotope data implies that such conditions may have obtained during an appreciable fraction of the accretionary period.

An alternative theory for explaining the isotopic abundance pattern of atmospheric neon (and xenon) is that the fractionation occurred during the loss of a primordial H_2 atmosphere captured from the solar nebula (Sasaki and Nakazawa 1988; Pepin, manuscript in preparation). This theory appears equally viable in terms of its ability to explain the isotopic data. It differs from the steam atmosphere model in that it requires that the accretion process proceed in the presence of nebular gas. If the lifetime of the solar nebula was much less than the accretionary time scale, as predicted by Safronov (1969), then the steam atmosphere model is preferred.

THE CONTINUOUSLY HABITABLE ZONE

A third reason that runaway (and moist) greenhouse atmospheres are of interest is that they set constraints on the inner edge of the continuously habitable zone (CHZ) around the Sun (Kasting *et al.* 1988; Kasting and Toon 1989). The concept of the CHZ was introduced by Hart (1978, 1979).

He defined it as that region of space in which a planet could remain habitable (i.e. maintain liquid water at its surface) over time scales long enough for life to originate and evolve. Hart concluded, based on what seems in retrospect to have been an overly simplified model, that the CHZ extended from only about 0.95 AU to 1.01 AU. In Hart's model, the inner boundary of the CHZ was determined to be the distance at which an Earth-like planet would experience a runaway greenhouse at some time during the last 4.6 billion years. The outer edge of the CHZ was the position at which runaway glaciation would occur.

The climate models described earlier (Kasting 1988; Abe and Matsui 1988) show that the runaway greenhouse threshold is considerably higher than Hart had estimated. If the minimum solar flux needed for runaway is 1.4 S_o (see above), then the distance at which this would occur should be < 0.85 AU. On the other hand, the minimum solar flux required to lose water in the moist greenhouse model is only 1.1 S_o. The radial distance at which this might occur is thus 0.95 AU, in agreement with Hart's original estimate. Thus, it appears that Hart located the inner edge of the CHZ correctly, even though his reasoning was slightly flawed.

The outer edge of the CHZ, on the other hand, probably lies well beyond Hart's estimate of 1.01 AU. Hart erred because he ignored the important feedback between atmospheric CO_2 levels and climate (Walker *et al.* 1981). This story is told in detail elsewhere (Kasting *et al.* 1988; Kasting and Toon 1989) and will not be repeated here. A modern conclusion, however, is that the CHZ is relatively wide, and that the chances of finding another Earth-like planet elsewhere in our galaxy are reasonably good.

CONCLUSION

Runaway greenhouse atmospheres are much better understood than they were several years ago. Recent theoretical work has provided better estimates of the amount of heating required to trigger runaway and new ideas about where such conditions may have applied. Future advances in our understanding of the evolution of Earth and Venus will require continued theoretical work in conjunction with new data on the isotopic composition of noble gases on both planets and on the water vapor distribution in Venus' lower atmosphere.

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