AN IMPACT TRIGGERED RUNAWAY GREENHOUSE ON MARS. T. L. Segura[1,2], C. P. McKay[2], and .O. B. Toon[1], [1]University of Colorado at Boulder, [2]NASA-Ames Research Center (MS 245-3, Moffett Field, CA 94035).

Introduction: When a planet is in radiative equilibrium, the incoming solar flux balances the outgoing longwave flux. If something were to perturb the system slightly, say the incoming solar flux increased, the planet would respond by radiating at a higher surface temperature. Since any radiation that comes in must go out, if the incoming is increased, the outgoing must also increase, and this increase manifests itself as a warmer equilibrium temperature. The increase in solar flux would correspond to an increase in temperature, which would increase the amount of water vapor in the atmosphere due to increased evaporation. Since water vapor is a greenhouse gas, it would absorb more radiation in the atmosphere leading to a yet warmer equilibrium temperature. The planet would reach radiative equilibrium at this new temperature. There exists a point, however, past which this positive feedback leads to a "runaway" situation [1]. In this case, the planet does not simply evaporate a little more water and eventually come to a slightly higher equilibrium temperature. Instead, the planet keeps evaporating more and more water until all of the planet's available liquid and solid water is in the atmosphere. The reason for this is generally understood. If the planet's temperature increases, evaporation of water increases, and the absorption of radiation increases. This increases the temperature and the feedback continues until all water is in the atmosphere. The resulting equilibrium temperature is very high, much higher than the equilibrium temperature of a point with slightly lower solar flux. One can picture that as solar flux increases, planetary temperature also increases until the runaway point where temperature suddenly "jumps" to a higher value, in response to all the available water now residing in the atmosphere. This new equilibrium is called a "runaway greenhouse" and it has been theorized that this is what happened to the planet Venus, where the surface temperature is more than 700 K (427 C).

Calculations and Results: From simple assumptions of optical parameters it is possible to calculate where this "runaway" point occurs in flux-temperature phase space. It is different for different atmospheric constituents and different values of available water. This point was calculated for the current Earth by [2] and found to be about 385 W/m^2. This indicates that if the solar and outgoing longwave fluxes of the Earth are greater than 385 W/m^2, the Earth could experience a runaway greenhouse. This increase in flux could be due to the simple steadily increasing luminosity of the sun. Let's say that a planet is perturbed a little: perhaps the temperature increases slightly due to some albedo effect: less ice cover leads to less solar flux reflected away, which leads to a higher temperature. If the effect is small, the planet will come to another equilibrium point as described above. The increased temperature will lead to an increase in evaporation which will increase the greenhouse and then increase the temperature. The planet returns to equilibrium at a higher temperature. If we now consider a large temperature perturbation, however, that perturbation may be large enough to increase evaporation so that the planet then "jumps" to the runaway regime, just as it did in response to a simple increase in flux past the runaway point. If the temperature of a planet increased a great enough distance in this phase space, it may be pushed beyond the runaway point and its new stable equilibrium point will be that of the runaway condition: all planetary water is in the atmosphere, none is on the surface, and the average temperature is very large due to the increased greenhouse effect. Preliminary analysis of the flux, vapor pressure, and temperature equations shows that such a stable solution is possible. Thus there are, in fact, *two* stable solutions in this phase space. One is the "normal" condition where the solar flux corresponds to some relatively low equilibrium temperature. The other is the "perturbed" condition where the same solar flux corresponds to a much higher temperature because a perturbation forced the planet to run away. To find these two solutions, a 1-D radiative convective model was run from two difference starting points, cold, and warm, for the same given incoming solar flux. The cold starting point lies on the “normal” branch (not the runaway branch) and corresponds to a planet with most of its water at the surface and little in the atmosphere with the atmosphere saturated. The model runs from this initialized state and the equilibrium temperature is noted. The warm starting point corresponds to a planet with all of its water in the atmosphere, and the atmosphere is consequently less than saturated. For solar fluxes less than the runaway value, both runs converge on the same equilibrium temperature. However, past a certain solar flux (and before the solar flux corresponding to the runaway point) both starts converge on *different* equilibrium temperatures. This means that if the planet is cooling down from a large temperature perturbation it will equilibrate on the hot “perturbed” temperature, which corresponds to the runaway branch, and will not fall to the “normal” branch, if the solar flux is sufficient enough. Ultimately, this analysis shows that a large perturbation could trigger a runaway greenhouse even if a planet's flux is below the threshold for runaway. One way a planet can experience such a large temperature perturbation is if it is struck by a large asteroid or comet. It has been shown previously [3, 4] that large impacts deliver large quantities of heat and energy to a planet and cause global-scale melting, evaporation, and precipitation of water. Models show that the temperature changes following an impact can be 1000s of degrees. This is probably enough to push the planet past the runaway point (as described above) provided that enough water were available, either as liquid water on the surface that would simply evaporate, or as surface/subsurface ice that could melt from the hot debris and then evaporate out. This research explores the different regions of phase space and speculates on how large an impact would be required for a given planet such as Mars. If this speculation is correct, any terrestrial planet could experience a runaway if struck by a large asteroid or comet.

References: [1] Ingersoll A.P. (1969) *J. Atmos Sci 26*, 1191 (1969). [2] Nakajima S. et al. (1992) *J. Atmos Sci. 49*, 2256 (1992). [3] Segura, T.L., et al., (2002) *Science 298*, 1977-1980. [4] Sleep, N.H. and Zahnle, K. (1998) *J. Geophys. Res. 103*, 28529.