

Comparing the Greenhouse Effect on Earth, Mars, Venus, and Titan: Present Day and through Time

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INTRODUCTION

The greenhouse effect has had a marked effect on the atmosphere-bearing worlds of the solar system. The most dramatic case is Venus with over 90 bars of CO₂ and surface temperature of 733 K rather than its equilibrium temperature of ~240 K (Pollack 1979). In contrast, Earth's greenhouse is relatively mild, currently providing ~33 K of surface warming, though this has been critical for maintaining the Earth as a habitable planet. Mars' greenhouse effect is a small 5 K, though evidence suggests it was substantially higher in the past (Carr and Head 2010). Interestingly, Titan's greenhouse shares many similarities with the Earth including a similar surface pressure (as opposed to Venus and Mars which have surface pressures ~100 times greater and ~100 time less, respectively) and the presence of a condensable greenhouse gas despite its chilling temperature (Coustonis 2005).

We can use comparative planetology to consider these worlds as an ensemble and probe the fundamental principles and consequences of the greenhouse effect. This kind of analysis can likewise give us insight about the potential atmospheres and surface conditions of atmosphere-bearing terrestrial exoplanets. In this endeavor we have more than simply the four data points of the current state of these worlds in the solar system, but we can also draw on the potential atmospheric conditions that existed on these planets in the past, which are constrained by geological, geochemical, and isotopic evidence and by fundamental physical limits.

The structure of this paper is as follows. First, we will discuss the basic physics of the greenhouse effect and greenhouse gas absorbers. Secondly, we will briefly explore each of the four worlds listed above. We will discuss the dominate greenhouse gas absorbers and processes, the atmospheric structures, and prevalent surface conditions. We will also explore some scenarios for past conditions, especially how these relate to compelling geological evidence for different atmospheric conditions in the past and the faint young sun paradox. Finally, we will tie

all these threads together and elucidate the fundamental physical processes involved in every planet and draw analogies between them. Note that this review is primarily qualitative.

GREENHOUSE GAS BASICS

Greenhouse gases are transparent in visual wavelengths, allowing the vast majority of the incident solar flux not reflected by clouds to reach the surface. They are opaque in the thermal infrared, creating a radiative forcing that causes the surface temperature to rise in order to preserve the planet in thermal equilibrium with the incoming solar flux.

The physical process by which atoms and molecules absorb radiation is somewhat complicated and involves heavy use of quantum mechanics for a rigorous treatment. However, we can qualitatively describe the process. Each atom or molecule has a suite of “states” corresponding to different quantized energy levels. A molecule can transition from a lower energy state to a higher energy state either by absorbing a photon or from an appropriately energetic collision. (Note that it is not necessarily the case that every possible higher energy state can be achieved directly from a given lower energy state and vice versa). Once in an excited state the molecule can de-excite to a lower energy state or the ground state (the lowest energy state) by emitting a photon or transferring some of its energy to a collision partner. There are three categories of transitions relevant to gas absorbers in Earth’s atmosphere. Those are, in order from highest energy to lowest, electronic transitions, vibrational transitions, and rotational transitions. Electronic conditions occur with energies in the UV range, while vibrational and rotational transitions occur in the near and mid-infrared. Ozone is an example of a UV absorber while water vapor has strong vibrational and rotational bands in the infrared. Since the thermal infrared is where the Earth emits the vast majority of its flux, the rotational and vibrational transitions are most relevant for determining radiative balance.

This isn’t the entire story because each absorption line has a profile dependent on the particle velocities (temperature) and the pressure. Changing these parameters can alter the equivalent widths spectral lines and thus change the net radiative forcing provided by the gas. Additionally,

we've yet to discuss yet another method of absorption relevant to very dense or very cool atmospheres, collisionally-induced absorption (known as CIA). The upshot of CIA is that it allows non-polar molecules (i.e. symmetric molecules without strong dipole moments) to absorb radiation. This works in one of two ways: 1) a collision induces a temporary dipole moment in the molecule, allowing absorption by a photon or 2) two molecules, for example N₂-N₂, are briefly associated as a bound supermolecule with its own quantized rotational states. These temporary molecules are called "dimers" (Hunt et al. 1983; Wordworth et al. 2010). The positive dependence on density is fairly easy to understand intuitively, the denser the gas the better the chance of a collision occurring in a given time. The negative correlation with temperature can be understood as a residence time effect – if a molecule has a lot of translational energy it will spend less time in the vicinity of another given molecule, so dimers are less likely to form.

Given a numerical value for the effective increase in radiative forcing, it is relatively simple to calculate a temperature change *absent any feedback effects*. You adjust the surface temperature so it radiates that extra energy into space (Hansen, Sato and Ruedy 1997). However, understanding climate feedback is crucial since negative feedbacks will act to stabilize the temperature while positive feedbacks will enhance the perturbation. The timescales for these feedback effects are also very important and vary substantially. It is often necessary to turn to general circulation models (GCMs) that incorporate all important feedback effects with timescales relevant to the calculation in order to make accurate predictions (Taylor 2010). Examples of feedback effects include temperature-dependent cloud formation (negative feedback, short timescale), the melting or formation of substantial ice cover (positive feedback, short/intermediate timescale), the carbon-silicate cycle (negative feedback, long timescale), and biological responses (varies).

GREENHOUSES IN THE SOLAR SYSTEM

Earth

The global, yearly averaged surface temperature of Earth is 288 K while the equilibrium temperature is 255 K. The equilibrium temperature is obtained by assuming radiative balance with the incoming solar flux according to the simple equation below:

$$T_{eq} = \left(\frac{S(1-A)}{f\sigma} \right)^{1/4} \quad (1)$$

where S is the solar constant (at earth \sim 1366 W/m²), A is the Bond albedo, σ is the Stefan-Boltzmann constant, and f is a geometric correction factor equal to 4 for a rapidly rotating planet , i.e. a rotation period on the order of days (Catling and Kasting 2013). Therefore the greenhouse effect is responsible for 33 K of warming (Pollack 1979) on Earth. The Earth as a whole must radiate the same integrated flux as a 255 K black body. However, greenhouse gas absorption primarily by CO₂ and H₂O redirects flux towards the surface, creating cool upper layers of the atmosphere. These layers radiate at a temperature significantly below 255 K and therefore to achieve the same integrated flux as a 255 blackbody the surface must become warmer to emit more thermal radiation. Most of this flux escapes through the 8-12 micron window (a relatively transparent wavelength region).

An important concept to emphasize as we continue is that a colder upper atmosphere is positively correlated with a warmer surface – the more radiation that the upper atmosphere is able to emit the less the flux that must come from the surface (Kasting 1984). Therefore we should expect worlds with larger differences between surface temperature and atmospheric temperature minimums to have more greenhouse warming. Hansen, Sato and Ruedy (1997) have shown that an increase in CO₂ of a factor of two is roughly equivalent to increasing the incident solar flux by 2%, neglecting feedback effects.

The primary greenhouse gas constituents for Earth are water vapor and carbon dioxide. Trace gases ozone, methane, and nitrous oxide also contribute (dePater and Lissauer 2007). Notably, while water is the biggest contributor to greenhouse gas warming, it is condensable and so is a “slave” to the non-condensable greenhouse gases, primarily CO₂ (dePater and Lissauer 2007). Water vapor can transfer latent heat to the atmosphere as it condenses, driving down the temperature gradient in the troposphere closer to a wet adiabatic than a dry one. Water is prevented from reaching the stratosphere and becoming photolyzed due to a tropospheric cold trap that condenses water vapor at the temperature minimum (tropopause).

Atmosphere evolution

The presence of sedimentary rocks and apparent absence of glacial deposits on Earth ~4 billion years ago suggests that the early Earth was warm, possibly warmer than today (dePater and Lissauer 2007). This is particularly problematic because the solar flux is believed to have been ~25% lower in the past. This problem is known as the “faint young sun paradox” (Goldblatt and Zahnle 2011). A possible explanation may be a much larger greenhouse effect than today. Atmospheric CH₄, CO₂, and H₂O and possible NH₃ were possibly larger at this time (de Pater). Many scenarios have been explored to explain this discrepancy including a much larger CO₂ partial pressure, substantial greenhouse warming by methane (Pavlov, Kasting, and Brown 2000), an organic haze layer, increased cloud cover, and increased pressure broadening from a significantly larger N₂ partial pressure and total atmospheric pressure (Goldblatt et al. 2009).

Venus

While Venus is often considered a sister world to Earth owing to its similar mass and size, its surface and atmospheric conditions are anything but Earthlike. The surface temperature and pressure are 733 K and 95 bar, respectively (de Pater and Lissauer 2007, Krasnopolsky 2011). Due to a high albedo from 100% cloud cover, the equilibrium temperature is ~232 K. The greenhouse warming on Venus is then a monster ~500 K. This isn’t too surprising since there are 92 bars of CO₂. Pressure broadening is significant at these densities and contributes greatly to the warming. CO₂-CO₂ CIA may also contribute; however, there has been no recent literature in this regime. The water vapor content is limited to ~30 ppmv (Meadows and Crisp 1996).

Atmospheric Evolution

It is often assumed that Venus began with a similar volatile inventory as Earth with a similar initial isotopic composition. If this is true the measured D/H ratio of over 150 that of Earth (Donahue et al. 1982) has been argued to indicate a massive loss of hydrogen in the past, presumably from photo dissociated water (Chassefiere et al. 2011), through Grinspoon and Lewis (1988) suggested that delivery of water by comets could explain this isotopic signature. In either case, Venus would have had oceans prior to entering its current runaway state if it contained a similar water inventory as the Earth (Kasting 1987). A runaway state cannot be

triggered by increased CO₂ (or any greenhouse gas) alone, but it typically thought to be caused by an increased solar flux (Kippenhan 1994) though internal heat flux causing a runaway for tidally active worlds is also possible (Barnes et al. 2012).

Kasting (1987) explored both the runaway and moist greenhouse limits of Venus. In the case Venus had an ocean in the early stages of its history; the solar flux at its present orbit would be such that it would almost immediately enter a moist greenhouse. There are two scenarios losing an ocean of water from increasing solar flux (Kasting 1987, Goldblatt et al. 2011, Catling and Kasting 2013). The first case is the runaway scenario; the ocean begins to evaporate into the troposphere increasing the net warming, but also increasing the pressure so the oceans do not boil. The water builds up in the troposphere much faster than it is photodissociated and the hydrogen is lost to space. Weathering reactions can still occur and act to sequester a buildup of CO₂. The temperature and water vapor pressure increases while the ocean persists until the critical point at 647 K at which point all of the remaining water evaporates and creates a dense water vapor atmosphere completely opaque to outgoing longwave radiation. The surface temperature then increases until it can emit effectively in the near infrared and visible where the H₂O opacity is much lower and cool. This corresponds to a temperature of ~1400 K, hot enough to melt the surface and bake out the carbon in surface rocks. Additionally, with no weathering processes CO₂ can continue to build up from outgassing in the absence of other sinks. In the second scenario, the release of water vapor into the atmosphere drives the temperature structure to be closer to isothermal, lifting the tropopause and removing the water vapor cold trap. The water vapor can now proceed into the stratosphere and become photolyzed. In contrast to the scenario above the water is destroyed at a rate commensurate with its evaporation from the ocean so runaway is not reached until after the water is lost. Once all the water is gone, the carbonate-silicate cycle shuts down. If there continues to be CO₂ outgassing from the mantle there is no obvious way to remove it.

Mars

Mars is in some ways at the opposite extreme of Venus in terms of temperature and pressure. The surface pressure is 6 mb and mean temperature is ~215 K (Carr and Head 2010). The equilibrium

temperature can be shown to be 210 K, so greenhouse warming is about 5 K or almost insignificant. The temperature can range from ~180 K to ~300 K depending on the latitude, season, and time of day (Carr and Head 2010). Technically, there are brief times today where liquid water could be stable on the Martian surface according to the phase diagram for H₂O. However, if we want to see a wet Mars we must look to the past.

Atmospheric evolution

Mariner 9 returned first photographs showing obvious fluvial features. The most common interpretation is that early Mars was warm and wet (Pollack 1979, Carr and Head 2010). Some mechanism, presumably the greenhouse effect (though an argument has been made for clouds), must have introduced enough radiative forcing to make Mars warmer earlier in its history. The problem is even worse than it first appears, since the Sun was ~25% fainter 3.8 billion years ago when clement conditions existed on Mars (Kasting 1991). Early Mars may have had a surface pressure on the order of 1 bar and a temperature close to 300 K (de Pater and Lissauer 2007).

Kasting (1984, 1991) showed that CO₂ alone cannot warm early Mars surface temperature to 273 K. CO₂ condensation into clathrate ice crystals modifies the atmospheric temperature gradient and causes the upper atmosphere to emit more thermal radiation. If the planet is in radiative equilibrium then the surface therefore emits less to get the same outgoing longwave flux, therefore the surface temperature begins to cool. So at pressures larger than ~5 bar CO₂ has a net cooling rather than warming effect. This is not enough given the solar flux at the time to warm the Martian surface above freezing. In this case CO₂ would condense in clathrates. Wordsworth, Forget, and Eymet (2010) presented a more rigorous treatment of the physics of CO₂ absorption in dense pure CO₂ atmospheres (including CIA) showing that Kasting 1984 actually overestimates the surface temperatures at high pressures, making the warm wet early Mars problem even worse. Other atmospheric greenhouse gas constituents in addition to CO₂ may solve the problem, or perhaps dust if it reduced the net albedo.

The possible warming role of CH₄, NH₃ and H₂S has been discussed (Sagan and Mullen, 1972). More recently SO₂ has been suggested as an early greenhouse warmer (Yung et al., 1997).

Titan

Titan's surface temperature and pressure are 93 K and 1.46 bar, respectively (coustenis). The atmosphere is dominated by N₂ with several percent CH₄ and about 0.3 % H₂ (Mckay 1991). Titan's tropopause is 71 K at 40 km.

Titan's greenhouse effect is primarily caused by the pressure-induced absorption of longwave radiation by N₂, CH₄, and H₂ (Mckay, Pollack, and Courtin 1991). H₂ absorbs strongly in Titan's window region (16.7-25 microns). CH₄ is analogous to water vapor on Earth because it is condensable under the conditions in the Titanian atmosphere. The greenhouse effect on Titan is dominated by the collisionally induced absorption of N₂-N₂, CH₄-N₂, and H₂-N₂ (Hunt et al. 1983; Wordworth et al. 2010). This stands in stark contrast to the atmospheres of Earth, Mars, and Venus where the dominate forms of absorption are vibrational and rotational transitions.

Titan also has a notable anti-greenhouse effect (Mckay et al. 1991). The antigreenhouse effect is caused by a high-altitude haze layer that absorbs at visual wavelengths but is transparent in the thermal infrared. The antigreenhouse effect acts to reduce the surface temperature by 9 K while the greenhouse effect increases the surface temperature by 21 K. So the net greenhouse effect is 12 K (82 K effective temperature vs. 94 K observed surface temperature). A Titan with no haze layer would be 20 K warmer due to the absence of the antigreenhouse effect and a stronger greenhouse effect (McKay et al. 1991).

Cooling of the surface is dominated by thermal emission in the 17-25 micron region of the spectrum. This is Titan's thermal infrared window. H₂ is important because it absorbs in this region much in the same way CO₂ is very important on Earth because it absorbs in the thermal infrared band of Earth's surface emission. It is likewise not limited by saturation.

Methane is close to the saturation vapor pressure, analogous to H₂O on earth.

Atmospheric Evolution

Due to reduced solar luminosity, Titan's surface temperature was likely 20 K colder than it is now 4 billion years ago (Mckay et al. 1993). In this case the N₂ in the atmosphere would have

been frozen on the surface in ice. The formation and longevity of Titan's atmosphere is an interesting problem with no solid solutions (Coustenis 2004). One problem is that with current rates of CH₄ photolysis and ethane production, the current reservoir of CH₄ in Titan's atmosphere would have been depleted in a time much less than the age of the solar system. Additionally, liquid ethane would have accumulated on the surface to a depth of several hundred meters at today's production rates (Lunine et al. 1989). Either it is an unusual time in Titan's history or there are unknown sources of CH₄ and sinks for ethane (Catling and Kasting 2013).

DISCUSSION AND CONCLUSION

Earth, Mars and Venus are similar in that they have significant atmospheres, weathered surfaces, past or present volcanism, and chemically differentiated interiors. Titan has a significant atmosphere, a weathered surface, possible cryovolcanism, and a potentially partially differentiated interior (dePater and Lissauer 2007).

Mars, Earth, and Venus all have greenhouses currently dominated by CO₂, though the magnitude of the warming and partial pressures of CO₂ vary by orders of magnitude. It is quite clear that both Earth and Mars must have had additional warming earlier in the Solar System's history when the Sun was less luminous. It is unclear what the source(s) of warming were (was) for these two planets, though many solutions have been proposed and a mélange of combinations are possible. Interestingly, Mars provides a comparative bridge to Earth's past since both planets provide ample geological evidence to suggest they were warmer beyond the limits of CO₂ greenhouse warming. In contrast, the early runaway greenhouse state of Venus provides insight into Earth's future as the solar flux continues to increase. By constraining models for all three planets simultaneously, knowing the fundamental underlying physical laws are the same for all planets, we may obtain solutions that would have been impossible if the Sun did not provide sister terrestrial planets.

Titan is an absolutely fascinating case study in this author's opinion, especially since, unlike the other worlds discussed, its greenhouse is dominated by collisionally induced absorption processes. CIA warming has many potential implications for the characteristics and potential

habitability of exoplanets (Pierrehumbert). Like Earth, however, Titan's atmosphere contains an abundant molecule close to its triple point, which is condensable in that atmosphere and therefore capable of modifying its temperature structure.

Major gas species in Earth's atmosphere are of course modulated by biology (Taylor 2010). Obviously this is not true for the other planets in the Solar System. However, we can use the contrast of the Earth system with the sterile worlds in our system to inform our understanding of other potential biospheres.

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