Atmospheres of different planets

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Introduction

Without Earth’s atmosphere, life as we know it would be impossible. To name a few of the reasons behind this, the atmosphere provides the oxygen we breathe, defends us against a constant bombardment of micrometeorites, protects us from dangerous radiation from the sun and traps the right amount of heat to make the planet inhabitable. Mankind couldn’t have designed a better atmosphere itself.

Other planets in our solar system, while forming under similar circumstances, have ended up with atmospheres in which humans cannot reside without an advanced space suit. To investigate how this could come to be the case, we will start by looking at what constitutes an atmosphere.

Since there are planets that are so vastly different than Earth, we will primarily be looking at the terrestrial planets since this will provide the most rewarding comparison. The terrestrial planets are the planets in our solar system that are primarily composed of silicate rocks and metals. Illustrated in Figure 1, this includes Mercury, Venus, Earth and Mars. While not technically a planet, we will also briefly mention the Moon.

Atmospheres

An atmosphere is a layer of gas surrounding a planet. This layer is in most cases surprisingly thin. On Earth, for example, about two-thirds lies on an altitude less than 10 kilometres above Earth’s surface.

Any atmosphere consists of a mixture of gases of either molecules or individual atoms. In the atmospheres of terrestrial planets the temperatures are generally low enough for the atoms to form into molecules. Some of the most common gases are nitrogen (N₂), oxygen (O₂), water (H₂O) and carbon dioxide (CO₂).

One important property of atmospheres is their pressure. Since the gravity pulls the gases downward, there are more molecules closer to the surface of the planet and fewer molecules at higher altitudes. Since this change is gradual, the boundary between the atmosphere and space becomes very difficult to determine. On Earth, however, at an altitude of about 60 kilometres, the molecules are so sparse and particle collisions are so rare, that it can’t really be thought of as air anymore. Because of this, an altitude of 60 kilometres is often considered as “the edge of space”. Of course, some molecules are present even above 60 kilometres. In fact, Earth’s tenuous upper extends for several hundred kilometres.

These are some of the ways that the planets affect their atmospheres, but atmospheres affect their planets as well. Apart from shielding it from radiation, scattering light to illuminate the planet’s sky and creating wind and weather, the atmosphere can contain certain gases, which heats the planet’s surface via the greenhouse effect. These gases are
called greenhouse gases and the most important are carbon dioxide (CO₂), methane (CH₄) and water vapour (H₂O). Because of their molecular structure, these gases absorb infrared light effectively and then reemits the light in a random direction, which means that it’s usually absorbed by another greenhouse molecule which does the same thing. In this manner, the greenhouse gases slows down the escape of infrared light from the lower atmosphere and their molecular motion heats the surrounding air, making the planet warmer than it otherwise would be. Since the interior heat of a terrestrial planet does not affect the surface temperature much, sunlight becomes its primary heat source and the greenhouse effect is therefore very important for a planet’s climate and habitability.

Calculating the theoretical average surface temperature of Earth without the greenhouse effect shows that it would be −16°C, compared to the actual temperature of +15°C. Since most of the water on Earth then would be frozen, it becomes evident that we would most likely not be able to survive without the greenhouse effect.

**Gaining an atmosphere**

A couple of billion years ago, when the terrestrial planets were forming, they were too small to capture any significant amounts of hydrogen and helium gas before it was dispersed by the solar wind. This means that the planets essentially were born without atmospheres and therefore the atmosphere gases must have been added at a later stage. There are in general three different processes that can add gas to a terrestrial atmosphere.

The most common process is volcanic outgassing. Even though the terrestrial planets mainly were formed by metal and rock, their interiors still contain some water and gas from impacts of ice-rich planetesimals, which can escape to the atmosphere during a volcanic eruption. The most common gases released by outgassing are water, carbon dioxide, nitrogen and some sulphur-bearing gases.

Some planets also have a secondary source of atmospheric gas, namely evaporation of surface liquids or sublimation of surface ices into gas. In most cases, these liquids and ices originate from condensation of gases from volcanic outgassing, but still continue to exchange gases with the atmosphere. And if the planet would heat up by some reason, this balance could change, resulting in more gas in the atmosphere.

On planets with a substantial atmosphere, these two processes constitute the only notable sources of gas. On small planets essentially unprotected by an atmosphere however, atmospheric gases can also come from a process called surface ejection. This is a process where micrometeorites, solar wind particles and high-energy solar photons can knock individual atoms or particles free from the planets surface into the atmosphere. This extremely low-density atmosphere would consist of the atoms and molecules knocked free from the surface and the particles that hit them.

**Loosing an atmosphere**

Planets can also lose atmospheric gases through five different processes. The first is condensation, where gases condense and fall as rain, snow or hail. On Earth we are used to rainfall consisting of water but this does not have to be the case on other planets. On Mars, for example, and especially at the poles, it is so cold that carbon dioxide condenses into solid ice, which constitutes most of the Martian polar caps.
Chemical reactions are also an important process that removes gas from an atmosphere and incorporates into a surface metal or rock. The most familiar example of this process is rusting, where oxygen is incorporated into iron. In fact, if it weren’t for the photosynthetic organisms that continually resupplies Earth’s atmosphere with oxygen, chemical reactions could remove all oxygen from the atmosphere within a few million years.

In contrast to both the chemical reactions and the condensation processes, which leave the possibility that the gases could return to the atmosphere, there are three processes that are permanent of which the first is the loss of gas through impacts. When a heavy meteorite creates a large crater on a planet, the blast is often powerful enough to hurl large amounts of atmosphere gases into space. While this effect is not as noticeable on larger planets where the gravity makes it difficult for gases to escape in this manner, all planets have probably lost a significant amount of gas this way.

The second permanent process is the solar wind, which on planets without a strong magnetosphere as on Earth, can sweep away some of the planet’s atmospheric gas. The third permanent process is thermal escape, which denotes the event of an atom or molecule in the atmosphere achieves escape velocity and flies off into space. The number of atoms leaving in this way depends mostly on three separate factors. The first factor is as with the loss of gas through impacts dependent on the size of the planet, which in turn affects its escape velocity. The second factor is the mass of the gas particles. Since gas particles have the same average kinetic energy at the same temperature, lighter gases receives a higher speed and is therefore closer to the escape velocity. The third factor is the atmospheric temperature. Higher temperature means higher average velocity and a greater probability of the particles achieving escape velocity. All the terrestrial planets are small and warm enough for helium and hydrogen to escape and thus they were unable to retain these gases from the solar nebula for long. Only Earth, Venus and Mars were able to retain some of the heavier gases, which is why they have significant atmospheres today.

The atmospheres of the Moon and Mercury

Often we don’t regard the Moon and Mercury as having an atmosphere at all but that doesn’t mean that they aren’t surrounded by gas. The thickness of their atmospheres, or rather the lack thereof, means that their atmospheres doesn’t even come close to having a complex structure like Earth’s. In fact, they only have a single layer with thin exospheres and if you could collect the entire atmosphere of either the Moon or Mercury and condense it into solid form, it wouldn’t be larger than a few cubic metres.

The reason that neither of them has a significant atmosphere is two-fold. Not only are they both so small that they have very low escape velocities, but also are the temperature of their surfaces and atmospheres so hot in the daytime that the average molecule velocity in the atmosphere is very high. (While the Moon isn’t as hot as Mercury, it is smaller so the result is approximately the same.) Furthermore, the volcanic outgassing has ceased a long time ago on both of them.
The atmosphere of Mars

Much evidence indicates that Mars once had a temperate climate as Earth has today, but has since seen a drastic change. Most of these changes can be explained by Mars’ smaller size. While Mars is only about 40% larger in radius than Mercury, this larger size leads to a much larger amount of volcanic outgassing, releasing water and gases into the atmosphere just as on Earth. But Mars was too small to maintain the internal heat needed to retain this water and gas. When its interior cooled down, the volcanic outgassing stopped and its magnetic field decreased in strength, allowing the solar wind to sweep away much existing water and gas into space. Some of the water molecules, however, have been broken apart by ultraviolet light, with the hydrogen atoms rapidly lost to space by thermal escape, leaving the oxygen atoms in the atmosphere. Over time, this oxygen was either swept away by the solar wind or absorbed by the surface rocks by chemical reactions, literally rusting the Martian rocks and giving the “red planet” its distinct colour, see Figure 2.

Today, the atmospheric pressure is only about 1% of that on Earth, resulting in a negligible greenhouse effect. This in turn has led to Mars having an average temperature of −50°C. This means that any water on Mars would be highly unstable and disappear rapidly, either evaporating or freezing to ice. But even with its small size, Mars might still have had flowing water if it was closer to the sun, where the extra warmth might melt the water that is frozen underground and at the polar caps.

The history of the drastic climate changes of the Martian atmosphere becomes more and more relevant for us on Earth as we stand in front of our own climate problems.

The atmosphere of Venus

Venus has an average surface temperature of about 470°C and because of its thick clouds, shown in Figure 3, which are very efficient heat transporters, the temperature is almost the same everywhere on the planet. It’s tempting to attribute this high temperature compared to Earth solely to the fact that Venus is closer to the Sun. As we will see, however, this is only indirectly part of the truth.

Venus has a surface pressure 90 times greater than on Earth and its atmosphere consists almost entirely of carbon dioxide. This results in a much greater greenhouse effect than on Earth. By calculating the theoretical average temperature without the greenhouse effect as we did before, Venus ends up being even colder than Earth. This means that most of the heating on Venus is due to its greenhouse gases. So the question is more about why Venus has so much more greenhouse gases than Earth and it turns out that the answer lies mostly in the fact that Venus is closer to the Sun.
As far as we know, Venus and Earth, being at approximately the same size, started out the same. That is, with volcanic outgassing creating an atmosphere of water vapour and carbon dioxide. However, most of the water vapour on Earth condensed into rain, forming our oceans and then the carbon dioxide dissolved into the water where it can undergo chemical reactions to create carbonate rocks, such as limestone. In fact, Earth has about 170,000 times more carbon dioxide in these rocks as in the atmosphere and the oceans themselves contain about 60 times as much dissolved carbon dioxide as in the atmosphere, leaving just the right amount of greenhouse gases in the atmosphere to make Earth inhabitable.

While Venus also may have had oceans once, the extra warmth from it being closer to the sun caused a larger part of the water being evaporated in the atmosphere. And because water vapour is a greenhouse gas as well, this further increases the temperature, which in turn causes more water of the oceans to evaporate and so on. This process is known as the runaway greenhouse effect. The water vapour would then gradually disappear by ultraviolet light breaking the molecules apart letting the hydrogen escape into space and the oxygen rusting the surface as on Mars. Without water, the carbon dioxide can't make carbonate rocks. Instead it's all still in the atmosphere.

Earth, on the other hand, was cool enough for water to rain down before the runaway greenhouse effect started. It turns out that while Venus’ distance to the Sun is only about 30% less than Earth’s, this difference was critical.

The atmosphere of Earth

The atmosphere of Earth, consisting of mostly nitrogen and oxygen, is the only atmosphere in which humans can live. We can conclude that Earth obtained this atmosphere mainly because of four reasons. The first is that Earth was able to retain most of its outgassed water because it was cooler than Venus and it was protected against ultraviolet light unlike Mars. The second is that Earth managed to move most of its carbon dioxide out of the atmosphere because of its oceans. The third is that the atmosphere consists mainly of oxygen, thanks to the photosynthetic organisms, and nitrogen, because that’s what remains when you remove the carbon dioxide and water. Finally, the fourth is that Earth has an ozone layer, also because of the photosynthetic organisms and oxygen, protecting it against ultraviolet radiation.

We can conclude that we are incredibly lucky that Earth is the size it is and as far from the Sun as it is, because small variations could have very serious consequences.
References

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