Storytelling with Uniview #09:
Atmospheres of the Terrestrial Planets

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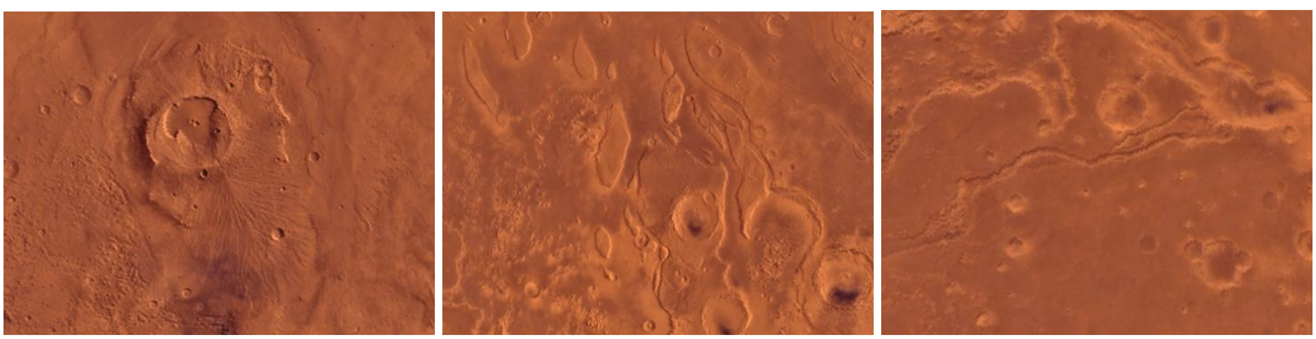
The inner planets of the Solar System—Mercury, Venus, Earth, and Mars—are often referred to as terrestrial planets. The name implies that they are Earth-like, although one could argue that Mercury is hardly very Earth-like at all, with its cratered surface, lack of atmosphere, and small size. But when you compare the interior compositions of the four rocky inner planets, they are very similar: they are made up primarily of silicate rock surrounding a metallic core. They have relatively thin (or no) atmospheres, at least when compared with the gas giants further out in the Solar System. And they are short on the lighter "volatile" gases, like hydrogen and helium.

Only Earth has a hydrosphere—sufficient amounts of water on or near its surface. However the three larger worlds (Earth, Venus, and Mars) all have evidence for water in their pasts. As is evident from features visible on the surface of the planet in Uniview (and also highlighted at the Stream Table interactive in the *Space Odyssey* exhibit), the Martian surface contains morphological features that suggest they were carved by running water. Yet Mars is very dry today, with what water remaining locked up in sub-surface ice. Venus is also extremely dry. How have these three worlds evolved over the history of the Solar System? Why has water stayed on Earth? What happened to the water on Mars and Venus? Let's take a look at our current understanding of (in order) Mars, Venus, and Earth.



Screenshots from Uniview of the features on the Martian surface that appear to be created by running water.

Brief History of the Martian Atmosphere

In addition to greenhouse warming, the size of the planet and other factors like the presence of a magnetic field are thought to be crucial to the evolution of its atmosphere. Mars is thought to have lost most of its atmosphere because it is too small and its gravity too weak. Large asteroid impacts gradually splashed more and more of the Martian atmosphere into space. Early in its history, Mars had a global magnetic field, which like Earth's, protected it from the solar wind. But because Mars is only one-ninth the mass of Earth, it lost its interior heat faster, its core cooled and solidified, and its magnetic field disappeared. Without a protective magnetosphere, energetic solar wind particles stripped away the bulk of the remaining atmosphere. As its atmospheric CO_2 dissipated, the planet froze. Martian water was lost via impacts and the solar wind, but also from ultraviolet light from the Sun. Because Mars does not have enough molecular oxygen to form an ozone layer, UV radiation can split water into constituent oxygen and hydrogen atoms. Hydrogen being the lightest element is also the easiest to escape into space. The oxygen was lost via the aforementioned atmospheric escape mechanisms, but also by chemical reactions with the surface rock, "oxidizing" it to give the Red Planet its rusty exterior.

Carbon Dioxide on Venus

Venus has as much CO_2 as Earth. But instead of it being located in the oceans or locked up in the rock, the CO_2 is in the atmosphere instead. Earth has oceans and a carbon cycle which regulates the amount of CO_2 in its atmosphere (see Earth section below). Venus does not have oceans so it does not have the same regulating effect.

Venus probably had as much water immediately after formation as Earth did, and like Earth, it increased its water reserves from comet and asteroid impacts. It may even have had water oceans early on. But because Venus was closer to the Sun than Earth and was heated more, the liquid water turned into water vapor, and rose into the upper atmosphere. Since water is also a greenhouse gas, its presence increased the surface temperature, which led to even more evaporation. This positive feedback loop resulted in a *runaway greenhouse effect*, which eventually led to all of the oceans turning into water vapor. Once in the upper atmosphere, each H_2O molecule could be split into hydrogen and oxygen atoms by solar UV radiation. The hydrogen, being so light, was lost into space; some of the oxygen was lost, while the rest got bound into the rocks. Even now, the Venus Express spacecraft orbiting the planet has detected hydrogen and oxygen atoms streaming out of the atmosphere.

Indirect evidence for Venus' water loss comes from measurements of deuterium to normal hydrogen—the D/H ratio. Since deuterium—which contains one proton and one neutron in its nucleus—is twice as heavy as regular hydrogen, it doesn't escape into space as easily. Deuterium on Venus is 135 times more abundant relative to hydrogen than on Earth, suggesting there was far more regular hydrogen in Venus' past. Based on evolutionary models of Venus' atmosphere, Venus lost almost all of its water in a billion years—so much so that it probably has at present 1/10,000th the water of Earth.

Climate Regulation of Earth

Although Earth has approximately the same amount of CO_2 as Venus, it never underwent a runaway greenhouse effect. Earth was far away enough from the Sun that water rained down and accumulated into oceans, instead of staying as water vapor in the atmosphere. The atmospheric CO_2 dissolved into the oceans, where most of it reacted to form carbonate minerals on the ocean floor. Earth's present-day oceans contain 60 times more CO_2 than what is found in the atmosphere, while there is even more CO_2 locked up in its rocks. In this way, CO_2 is recycled in a "carbon dioxide cycle" or "carbon-silicate cycle":

1. CO_2 from the atmosphere dissolves in the oceans.
2. Rain falling on land "weathers" or erodes silicate rocks, which eventually flow into the oceans.
3. The silicate minerals react with the dissolved CO_2 to form carbonate rock. These build up on the ocean floor.
4. Plate tectonics carry the carbonate rock into subduction zones, where it is pulled in a conveyor belt-fashion into the mantle.
5. Once in the mantle, the melting carbonate rock releases CO_2 back into a gaseous form, from which it can be outgassed back to the atmosphere via volcanic eruptions.

This carbon dioxide cycle helps regulate the Earth's temperature like a thermostat on a timescale of millions of years. This is because the rate at which carbonate minerals forms is sensitive to temperature:

- If the Earth gets a bit cool, less water evaporates from the oceans into the atmosphere to form clouds. Rainfall decreases and weathering of silicate rocks slow. Formation of carbonate rock also slows, and the chief method for reducing CO_2 in the atmosphere slows as well. However volcanoes continue to pump out CO_2, and do so until the greenhouse effect warms the planet enough to increase weathering again.
- If the Earth warms a bit, more water evaporates from the oceans, which leads to more rainfall. This increases the silicate weathering, which results in more of the atmospheric CO_2 getting locked into carbonate rock. The reduced CO_2 leads to less of a greenhouse effect, so the Earth cools a bit.

Thus if the Earth warms, the CO_2 cycle will tend to cool the Earth. Conversely if the Earth cools, feedback from the cycle will pull the Earth in the other direction and warm it. From stellar evolution models, we suspect that the early Sun had only 70% of the present day Sun's luminosity. The carbon-silicate cycle just described is one explanation for how the early Earth could have stayed warm enough for liquid water to exist. It also explains how the planet could have escaped from the multiple "Snowball Earth" episodes in the pre-Cambrian when most of the globe froze over from pole to pole. Once weathering to lock up CO_2 in the rocks stopped, it took about 10 million years for volcanic activity to build up enough CO_2 in the atmosphere to create a strong enough greenhouse effect to melt the ice.

However the carbon dioxide cycle does *not* help us from the effects of the increased CO_2 in the atmosphere from the fossil fuels that humans are burning. The recycling time for CO_2 via the carbon-silicate cycle is on the order of half a million years—much too long to help us.

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As we have seen in this brief review, the atmospheres of the terrestrial planets have undergone substantial changes since their formation at the beginning of the Solar System 4.5 billion years ago. The factors that affect this evolution include not just the proximity of the planet to the Sun, but also the amount of UV radiation from the Sun, the effects of solar wind, impacts from asteroids and comets (which can add volatile gases as well as cause gases to escape the atmosphere entirely), the presence of a magnetic field, the presence of plate tectonics, and even the geological make-up of the planet's surface.

The evolution of a planet's atmospheres is a complex topic, with negative and positive feedbacks. Planetary scientists build sophisticated computer simulations of an atmosphere, taking into account all of the aforementioned factors (plus many more). As a check on the models, we have not just one but three planets to compare the simulations to. The computer code that is used to show how Earth's climate evolves with increasing anthropogenic CO_2 in its atmosphere can be used—with the right adjustments to the input parameters—to show why Venus and Mars have the surface temperatures they have today. The underlying physics doesn't change, but the variables do. This "comparative planetology" approach is one way in which we can have some confidence that our simulations are on the right track.

References

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