Dune and Superdune

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Dune. No further elaboration is needed for the readers of this magazine. The recent movie, a huge improvement on the almost forgotten [Forgotten? No way! –Ed.] 1984 version, has solidified a profound vision of the environment of Arrakis in the public imagination. A world of heat, sand, intrigue, and terror. The sequel is eagerly awaited.

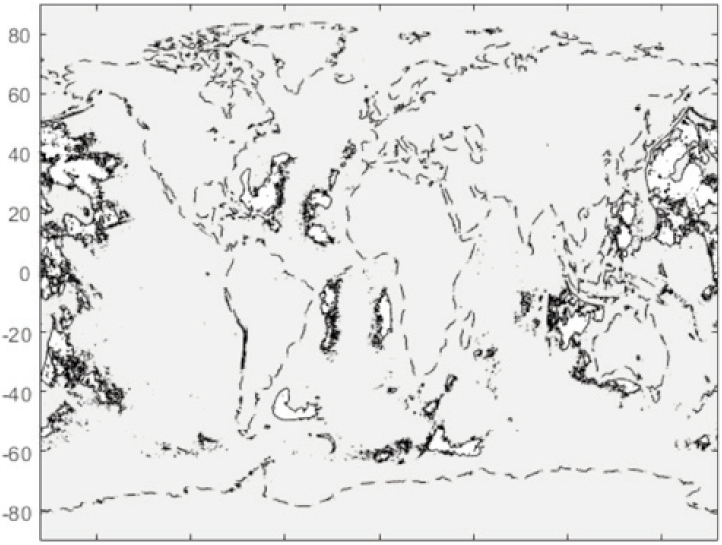
Arrakis is a world with almost no surface water. In contrast, about 70% of Earth's surface is covered by water. Numerical simulations of planetary formation show that this is not unusual, and indeed waterworlds with 100% water coverage should be common. Also, though, there should be temperate worlds about the size of Earth that receive about the same amount of solar radiation but that have considerably less water.

How much less? Earth is about 0.02% water by mass, counting all of the oceans and ice caps plus a substantial but rather uncertain amount of water locked up in the Earth's interior. For stars the size of the Sun, numerical simulations routinely generate worlds with a tenth of this water. With a hundredth. With a thousandth. There are even some with less than one millionth. While these simulations are not very well constrained by available observations and theory, they do have the ability to create planetary systems similar to our own and other star systems, so that at least provides us with a first cut at the kind of worlds that might exist.

To see what a hierarchy of dry planets might look like, we can conduct a thought experiment. We start with the amount of water on the surface of Earth and then gradually reduce it by orders of magnitude and see what kind of world is produced. A short Matlab program combined with a dataset of topographic heights and ocean depths is used to calculate the ocean depth that would occur if the ocean volume were reduced. Let's start this experiment with a planet that has one-tenth the amount of water that Earth has. As a first approximation, we will assume that this leads to an ocean mass that is also less by the same ratio. With this amount of surface water, the oceans have now become a collection of largely disconnected seas. The biggest one is still quite large, though, with the new Pacific Sea still occupying the majority of the area currently covered by the Pacific Ocean. Typical ocean depths are now only a few hundred meters to a little over a thousand meters. The percentage of the surface covered by ocean decreases but by less than you might think, from its current value of 71% to about 34%. This is because the distribution of topographic heights on Earth is bimodal: there is a peak in the frequency of heights at about the current sea level and at slightly higher elevations, and another peak at the typical ocean depth. Heights in between these two values are considerably less frequent. On this drier world, this means that many of the new seas continue to hug the present-day continental coastlines, so surrounding the new sea level of this world would often be some rather scary cliffs and ridges, sometimes thousands of meters high. The coastal sea level plains of Earth would now be some 4200 meters above the new sea level and would become high desert regions, a bit like the Andean altiplano. It is possible that there would also be extensive ice caps in some of these regions, including even in equatorial places like New Guinea, since there is already a glacier there in the current terrestrial climate. These high regions would also have much lower atmospheric pressure than they do at present. Some very elevated regions like the Tibetan plateau would become uninhabitable due to the oxygen pressure there becoming too low to breathe. These regions of unbreathable atmosphere would be even larger if the mean atmospheric pressure on this new Earth-like world were lower than on Earth to begin with. A kind of world would be created where roaming the large elevated areas would be like visiting another planet, a so-called "harandra" world, a word used by C.S. Lewis to describe the uninhabitable elevated plateaux of Mars in his fictional version of the planet. Even so, there would still be plenty of precipitation in many regions and tropical rain forests near the new sea level might not be unknown.

Reduce the water content to one hundredth of Earth's and the picture changes again (see map). The oceans are now still fairly large seas but are geographically restricted and rather shallow. The percentage of the surface covered by ocean decreases dramatically, to about 9%. The biggest and deepest seas are still in the north Pacific, where there is a large patch of contiguous water about the size of the continental U.S. There are other smaller disconnected seas in parts of the Atlantic and Indian oceans. While there would be some isolated regions downwind of the seas that would be well-watered and temperate, there would also now be some large desert regions, including at equatorial latitudes where deserts are very localized on present-day Earth. Mars is a bit like this: while it has next to no surface liquid water, the total amount of surface ice on the planet is about one hundredth of Earth's total surface water and ice, and there is also plenty of ice not far beneath the surface in many locations. Welcome to "desert world."

At one thousandth of the Earth's water content, seas cover less than 1% of the surface and are now small: they are more like lakes and only about three of them are larger than Lake Superior. For this geography, it starts to become debatable whether this small amount of surface water



Ocean coverage for a world with one hundredth of Earth's ocean volume. Ocean areas are light. The terrestrial sea level is indicated by a dashed line and is at a height of 5300 meters for this topography.

would be sufficient to maintain a steady-state ocean-based hydrological cycle, the interplay between evaporation, precipitation and river runoff that on Earth results in a more or less constant volume of ocean water. The possibility exists that a significant fraction of the available evaporation from these lakes might fall as precipitation elsewhere, disappearing underground and never making it back to these small, isolated salt lakes. Eventually, this could lead to the lakes drying up and the effective end of large areas of precipitation. Subsurface water would not disappear entirely, though: it could still percolate to the surface here and there if the local geological and soil conditions were favorable. Some decent sized lakes and ice caps might also be possible in polar or very elevated regions, where evaporation is much lower, and lakes would be continually fed by meltwater from glaciers. This could be an "oasis world."

Finally, what would an Earth-sized world with one millionth of Earth's water look like? Well, it might look a little like Mercury, but with a much thicker atmosphere and without Mercury's ubiquitous craters. Mercury is currently estimated to have up to about a trillion tons of ice locked away in shadowy parts of its polar regions, and that would be approximately the mass ratio of water to planet for our hypothetical one-millionth water world. Such a world might have some polar ice but little or no surface or subsurface water elsewhere. This is worse than on Arrakis, where at least the inhabitants have access to subterranean aqueducts ("qanats"). Call it "Superdune."

Even drier worlds are possible. Indeed, simulations indicate that planets with a billionth of Earth's water appear to be quite frequent: great dreary deserts with nary an oasis in sight. Since planets with global oceans are called "waterworlds," these hyperarid worlds could be called "nowater worlds." Even so, while these worlds would have only a thousandth of the water of Superdune, a thousandth of a trillion tons of ice is still a billion tons of ice. That is about the same as the estimated amount of water ice in the polar regions of the Moon, where it is considered a large and potentially valuable resource. Nevertheless, there might be some worlds, hotter ones, where even this amount of water would have been evaporated and driven off at some stage.

This thought experiment is pretty simplistic, of course. Other planets will have different geographies, just as Earth has had in the past, with the arrangement of its continents ranging from widely separated to all clumped together. Very recent work has suggested that the continents might have been formed by a series of giant impacts, and this random process could have caused them to have very different sizes and locations. A planet with considerably less water might have a different geological evolution, so the distribution of the topographic heights of the continents might not be similar to Earth's. The evolution of its atmosphere and climate would also vary, and a change in sea level would not be the only climatic effect that would need to be taken into account.

Now back to Arrakis. Some literary-minded scientists based in Britain have recently simulated its climate. They do this by using climate models that solve physical equations based on our understanding of atmospheric physics to calculate the weather and climate of a planet. For Arrakis, certain assumptions have to be made. For instance, its topography had to be specified, and this was done by careful reading of the text of *Dune*. The Great Flat was assumed to be low-lying and close to the equator, while the planet's capital Arrakeen was placed in a more elevated region in the northern mid-latitudes. Atmospheric composition was assumed to be similar to Earth's, except that the books state that ozone is known to be at a much higher concentration on Arrakis. Also, of course, water vapor would be a lot less than on Earth. These and other numbers were plugged into a climate model on a supercomputer, and after a few weeks of hard simulation, the climate of Arrakis was generated. The data can be viewed at https://climatearchive.org/dune.

For the most part, these results have some similarities to the climate described in the book. But the simulated climate of the capital Arrakeen is quite extreme: if we assume that it is located in the foothills of the northern mountains, July averages there would be more than 35 degrees C, or hotter than Las Vegas, and January averages might be around minus 20, or similar to Winnipeg or Irkutsk. On Earth, such an extreme seasonal variation in temperature is typical of land locations that are very distant from oceans and located at higher latitudes, like Siberia for instance. On Arrakis, plains in the more poleward regions of the mid-latitudes have the worst climate, with summer averages above 50 degrees C and winter averages typically below minus 40, making them essentially uninhabitable. Another difference from the book is that the climate model suggests that in fact there would be some rain on Arrakis, but only at non-equatorial latitudes in the mountains and mostly in the warmer months. This would include the high mountain regions surrounding Arrakeen. Even so, rainfall amounts there would still be low, perhaps at most one hundred mm (a few inches) for the entire rainy season at some of the higher elevations. Meteorologically, the most likely weather type that would cause this kind of precipitation would be isolated afternoon and evening thunderstorms, so the valleys between the mountains could contain dry riverbeds (wadis) that would be subject to occasional flash floods. The crucial point here is that a little precipitation can occur even on a planet that has no surface water, provided that it has some water vapor in its atmosphere. This highlights another difference from the book: the climate simulations imply that there should be no polar ice caps. The problem is that the simulated summer temperatures in the polar regions are far too high for ice caps to be present. On Earth, the survival of polar ice caps depends on low summer temperatures. The current arrangement of the continents assists this, with Antarctica completely surrounded by cold oceans that suppress summer warmth and the Arctic Ocean having the same effect in the Northern Hemisphere. With higher summer temperatures, these ice caps could disappear, which already appears to be happening in the Arctic. This would not be such an issue on a planet with only a small tilt in its axis of rotation and therefore no seasons, as since there would be no summer, polar caps on dry worlds would be more stable. Naturally, all of these numbers are very rubbery and depend on the precise details assumed for the geography of Arrakis. Also, like all models, the climate model used here almost certainly has some inaccuracies, particularly in its simulation of precipitation.

The availability of water appears to be an important prerequisite for the development of life, so a world without water would likely be lifeless, with an oxygen-free, unbreathable atmosphere. On Arrakis, the strange combination of a world without surface precipitation but with a breathable atmosphere is explained as a result of the invasion of an exotic biological species, the sandtrout, a metamorphic stage of the giant sandworm. The sandtrouts grab all the water for themselves, and as a result the lakes and oceans of Arrakis have dried up, leaving the breathable atmosphere behind. But strange extraterrestrial biology is not the only way to produce a no-precipitation world with an atmosphere that still contains lots of oxygen. There are also ways that have nothing to do with biology at all.

Some recent work has indicated that water vapor can be broken up into hydrogen and oxygen by intense stellar radiation, and given the right conditions the oxygen can stay in the atmosphere for a long time. This gives a nonbiological way of creating an oxygen-rich atmosphere. Recent numerical simulations by Joshua Krissansen-Totton and coworkers, using a complicated model of geological and atmospheric evolution, have suggested that dry worlds with such atmospheres are possible. The initial planetary conditions for this model are varied, and it is then run forward in time from the formation of the planets to more than 7 billion years later. The resulting worlds provide a surprising insight into the typical types of Earth-sized planets that might form around a star like the Sun.

The starting point is the initial composition of the planets. This is known to vary considerably, and in their work the effect of differing initial amounts of carbon dioxide and water was examined. Initial water amounts ranged from about 0.05 times the amount of water in Earth's current surface ocean to about two hundred times, values that span some of the likely range of water amounts that would be accumulated in typical Earth-sized planets. We focus on the planets with less initial water, as naturally enough these are the ones most likely to end up as desert worlds and least likely to become waterworlds.

After several billion years of simulations, most of these desert planets end up without oxygen. A subset, though, end up with ocean depths ranging from nothing to two hundred meters and oxygen pressures ranging from about ten millibars to several thousand millibars (the typical Earth atmospheric pressure at sea level is roughly one thousand millibars, with an oxygen pressure of roughly two hundred millibars). An oxygen pressure less than about seventy millibars would probably be insufficient to sustain human life for an extended period of time, although the exact value of this threshold pressure is a gray area. This is roughly the oxygen pressure at the lower boundary of the Himalayan mountaineering "death zone" above eight thousand meters. An oxygen pressure greater than about one thousand millibars would be toxic to humans for long exposure, although lower pressures could also be problematic. For an atmosphere to be breathable, other gases would also have to be at nontoxic concentrations, in particular carbon dioxide. For these dry worlds, most simulations ended up with relatively low levels of carbon dioxide, mostly less than one millibar, which would not be toxic. So, all in all, it appears at least possible to generate a very dry world with a breathable atmosphere.

There is another, unexpected advantage of a desert world: it has a larger habitable zone, the Goldilocks region of a stellar system where it is not too hot and not too cold. Ocean planets have lots of water vapor in their atmospheres, and water vapor is a greenhouse gas. Too much water vapor and too much incoming solar radiation means that a planet could heat up uncontrollably, eventually ending up like Venus. Since the inner edge of the habitable zone is set by the onset of these so-called runaway greenhouse conditions, this boundary would occur at a lower amount of incoming solar radiation for worlds with a lot of water vapor. In contrast, it is more difficult to initiate a runaway greenhouse on a desert world. Calculations suggest that for a desert world, the inner edge of the habitable zone in a system like our Solar System is considerably closer to the Sun than for a planet like Earth. This also means that as stars like the Sun increase in brightness with age, desert worlds will maintain their habitability longer than worlds like the Earth.

Are there any real examples of extrasolar desert worlds that we know about yet? No, but there may be ways to identify them. For example, desert worlds would of course typically have much less water vapor in their atmospheres than ocean worlds, and in principle this could be identified by using a large telescope to take spectra of their atmospheres. Their land areas would also be more reflective: this sounds a little counterintuitive, but the reflectivity of oceans is considerably less than that of deserts, unless the light is reflected off the water surface at a specific angle. Desert worlds would also have a lot fewer clouds, and this could be detected as well.

Strictly speaking, the planet LHS 3844b could be called a desert world of some kind. This Earth-sized planet orbits the red dwarf LHS 3844 in the constellation Indus at a distance of only 15 parsecs. It is located so close to its star that gravity likely forces it always to keep the same face toward its star, just as the Moon keeps the same face toward the Earth. It is now known that it does not have a substantial atmosphere because the temperatures of its day and night sides have been measured by the Spitzer Space Telescope. In the paper that announced this discovery, the dayside was measured at about 1,040K, or hotter than Venus, while the nightside temperature is described as being "consistent" with absolute zero. These values have a very large range of possible temperatures, and in reality the night side is certainly warmer than that. This extreme difference in temperature between the day and night sides strongly implies that the planet does not have an atmosphere that is thick enough to transport heat from the dayside to the nightside to smooth out some of this temperature imbalance. A thin atmosphere combined with high temperatures most likely implies no water on the dayside, although for all we know the nightside could be covered in ice caps or it could just be mostly bare plains like the Moon.

Of course, desert worlds are not the only types of worlds that can be generated. The simulations reported by Krissansen-Totton and his coworkers reveal a rich spectrum of possible Earth-sized worlds. A few of the most typical are described here:

A lifeless but temperate Earth with little or no oxygen. These planets may have decent oceans of varying sizes and some would be reasonably hospitable as a result, although many would be hot compared to Earth. Earth itself used to be like this before the onset of atmospheric oxygenation caused by life.

A hot steam world with a thick atmosphere of water vapor and carbon dioxide and a surface pressure several hundred times that of Earth. Surface temperatures well in excess of 1,000K are common.

A hot oxygenated steam world. In this scenario, non-biological oxygen production is assisted by plenty of water and intense solar radiation. These worlds are very hot but tend to be cooler than the hot steam worlds (about 600–1,000K or so, or in the ballpark of the temperature of

Venus).

An ice world. Typical global average temperatures are less than 230K (minus 40°F), along with a thin atmosphere dominated by nitrogen and carbon dioxide.

A greenhouse world that is temperate only because of a large, toxic concentration of carbon dioxide, causing an enormous greenhouse effect that compensates for this planet receiving less solar radiation than Earth.

A hot ocean world. At high atmospheric pressures, liquid water can be present on the surface at high temperatures. Here, typical mean temperatures are about 500K, well above the boiling point of water at terrestrial sea level. This is accompanied by a thick carbon dioxide atmosphere along with lots of water vapor.

Finally, consideration of the environment of a desert world is not entirely academic, as Earth itself is likely to become one in about a billion years or so. As the Sun becomes brighter, temperatures on Earth will inevitably increase. Ocean loss will occur and desertification will be the likely result. This will not be a rapid process, though, so the desert planet stage will probably last for a long time. This suggests that planets similar to a future, desert Earth might eventually be detected orbiting some of the older, nearby stars that used to be Sunlike but are now evolving toward red giant status—61 Virginis comes to mind immediately, as this nine-billion-year-old star already is known to have some planets. On a future Earth, evolution will therefore favor species that are able to live in a very dry environment. Sandworms would be right at home.

Acknowledgments

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Further reading

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Krissansen-Totton, J., Thompson, M., Galloway, M.L., and Fortney, J.J., 2022. Understanding planetary context to enable life detection on exoplanets and test the Copernican principle. Nature Astronomy, 6(2), pp. 189-198.

This paper is open access and has a nifty video of the planetary simulations.

Tian, F., Ida, S., 2015. Water contents of Earth-mass planets around M dwarfs. Nature Geoscience, 8, pp. 177–180. https://www.nature.com/articles/ngeo2372

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