Science Fact

Drycanes and WASPs

Kevin Walsh

Most of the time, Earth is a friendly place, weatherwise. The Sun shines, it rains but not too much or too little, and it is not too hot or too cold for human beings and other life to flourish. Naturally, some places are more hospitable for macroscopic carbon-based life than others—Tahiti is better than the North Pole. Also, one creature's paradise could be another's hell, as orangutans prefer very different places than those favored by polar bears. But on the whole, our planet is hospitable. This is not surprising, as we have evolved to fit Earth's climates and habitats.

Even so, Earth has some nasty weather. Hurricanes can smash coastal cities. Tornadoes can destroy inland towns. Blizzards can bury entire regions and make them impassable for days. Heat waves can kill hundreds. But such weather is extreme precisely because it is rare. Most of the time, our weather is benign.

On other planets in our Galaxy, maybe not so much. By galactic standards, Earth has a narrow range of temperatures and other weather variables. On many other planets in our Galaxy, the weather is much worse.

The most Earth-like planet in our Solar System is Mars, but this desert world is still very inhospitable. Apart from the very low surface atmospheric pressure and brutally cold nights, there are dust devils that charge across the desert like mini-tornadoes, as well as larger dust storms that can end up covering the entire planet. While the thin atmosphere on Mars almost entirely prevents its winds from causing substantial damage, the fine dust on its surface is easily lofted into the air. The future inhabitants of Mars will probably curse this dust, as it will likely get into practically everything.

There might be a few planets in other solar systems that are more hospitable. Assessment of actual weather conditions on exoplanets is a developing field, which is a polite way of saying that we don't know much about it. Nevertheless, recent work performed with numerical simulations has led to some surprising outcomes.

Take a planet circling a run-of-the-mill, dime-a-dozen M star, the red dwarfs that outnumber all other types of stars. Many of the worlds circling these stars will be tidally locked, with one side perpetually facing their star and the other side facing away. This would give very different climates between the dayside and the nightside—although not so different as we used to think. Previously, it was often assumed that planets like this had baking hot daysides and nightsides with temperatures that would make our South Pole seem balmy by comparison. Recent work has challenged this picture. If the planet has an Earth-type atmosphere, a lot of heat can be transported from the dayside to the nightside, thus reducing the temperature difference. These worlds may then have habitable regions that are considerably larger than previously thought.

Even though such a planet doesn't have a day-night cycle, it still rotates. This just means that its rotation period is the same as its orbital period, known as synchronous rotation. For synchronously rotating planets orbiting M stars, their rotation periods would vary: a world orbiting an M star within its habitable zone would typically have a rotation period of around thirty days for larger M stars but only about ten days for smaller ones. Some of these planets might have other rotation periods: for instance, they might be like Mercury and rotate three times for every two orbits, locked into a so-called nonsynchronous orbit. These worlds would have long solar days rather than no day-night cycle, and for planets with Earth-like atmospheres there would be very substantial differences between daytime and nighttime temperatures. Nonsynchronous rotation requires an oval-shaped rather than circular orbit, as an oval orbit would cause a variation in tidal force from one part of the orbit to another. This would allow nonsynchronous rotation in much the same way that Mercury's rotation is maintained. Irrespective, both synchronous and nonsynchronous planets have rotation periods of many days, rather than no rotation.

This non-zero rotation is important for a planet's weather. Lots of weather systems on Earth rely on forces generated by rotation. In particular, the Coriolis effect is caused by the different speeds of rotation of the Earth's surface, as the Earth's equator moves fastest but the North Pole not at all. We surface dwellers don't notice this rotation, of course. A pedestrian strolling through Central Park doesn't realize that the park is rotating at about 1300 kilometers per hour, because they are moving at the same speed. But a parcel of air moving from the North Pole toward New York City would be moving into a region where the surface is moving faster than the location it came from, so the parcel of air would get left behind. To us surface dwellers, it would seem as if the parcel were being pushed to the west, in the direction opposite to the rotation. The parcel's trajectory would then become curved. This twisting motion provides an important driving force for twisty weather systems like mid-latitude lows and hurricanes.

In principle, the rotation of M-star planets could provide enough Coriolis for hurricanes to develop. Hurricanes can be simulated by climate models but not easily, as they are small compared with the radius of the Earth and have strong wind gradients. To obtain a good simulation of them, fine resolution models are needed, with grid points ideally separated by only a few kilometers. Running such a model over the entire globe is hideously expensive in computer time, and to date only a few studies have tried to do that. But reasonable simulations of hurricanes can be obtained with grid points separated by tens of kilometers. These simulations are much less expensive, although the relatively coarse resolution ensures that the very extreme winds observed close to the eye in real hurricanes are absent in the simulated ones. Nevertheless, these more modest simulated tropical cyclones share many of the features of observed ones, and we can learn a lot from their behavior under different climate conditions.

This was the motivation for a study published in 2020 by Mingju Yan and Jun Yang of Peking University. They used a climate model with a resolution of about 50 km to generate hurricanes on Earth-sized planets of M stars. Rotation periods of these planets were varied from six to forty days. A synchronously rotating world with a rotation period of 6 days and receiving about the same amount of stellar radiation as Earth would circle a very small M star. If the planet had a rotation period of forty days, to experience Earth-like stellar radiation, it would have to orbit an M star almost large enough to be a K star. In this study, the numerical experiments assumed a worldwide ocean with fixed sea surface temperatures. Various simulations were performed, with the highest dayside temperatures specified to vary from 315K (about 108°F) to 301K (about 82°F, or roughly the ocean temperature in Earth's equatorial regions). Nightside temperatures varied from 310K (about 99°F) to 268K (about 23°F, or below freezing).

The results show that not all of these planets have hurricanes. The ones most likely to have them are fast spinning, warm planets—in other words, those near the inner edge of the habitable zone of smaller M stars. For these planets, if the ocean is warm enough, hurricanes can form even on the nightside. They also last a lot longer than terrestrial hurricanes, up to fifty days—not surprising, as these are ocean worlds, and one of the reasons Earthly hurricanes die is if they travel over land. As on Earth, these M star hurricanes don't form very close to the equator, as there is no Coriolis effect there, due to the weak north-south gradient in rotation speed at that latitude.

Interestingly, planets with relatively rapid, six-day rotation periods, but where the maximum surface temperature is reduced to values similar to Earth's tropics, have few hurricanes. An example would be a planet near the inner edge of the habitable zone of a small M star but with a weak atmospheric greenhouse effect, making its surface temperatures cooler than they would be for an Earth-like atmosphere. Also, planets with rotation periods of forty days have fewer hurricanes, even if they have high dayside temperatures. This shows how crucial both rotation rate and surface temperature are for the formation of tropical cyclones.

One curious result in Yan and Yang's work is that for certain atmospheric compositions, hurricanes don't form at all. For instance, a planet with an atmosphere of hydrogen and helium has no hurricanes. On Earth, hurricanes rely on showers and thunderstorms to maintain their intensities, so they need water vapor. Water vapor is less dense than air, so a parcel of air with more water vapor in it will rise, thus promoting the vertical motion that aids the development of thunderstorms. In contrast, water vapor is denser than either hydrogen or helium, so in an atmosphere dominated by hydrogen or helium, a parcel of moist air would sink. This would kill the upward buoyancy needed to sustain showers and thunderstorms, and so would also kill a hurricane.

Similar results were found in a 2020 study by Thaddeus Komacek of the University of Maryland and collaborators. Instead of directly simulating hurricanes, they used a coarser-resolution climate model to simulate whether the atmospheric conditions on such planets would be favorable for hurricane formation or not. They found a maximum formation rate at a rotation period of eight days, with both faster and slower rotators having fewer cyclones. Faster rotators were expected to have more hurricanes, so this was a surprise. More recently, in 2024, Valeria Garcia of the University of Washington and her colleagues used a similar modeling system to that used by Yan and Yang. Like Komacek's study, they also found that the maximum number of tropical cyclones occurred at a rotation period of eight days. As expected, slower rotating planets had fewer cyclones, but as in Komacek's study, they also found the planets rotating the fastest, those with periods of four days, had fewer tropical cyclones. This is because while faster rotation increases Coriolis, it also makes other atmospheric conditions more hostile to hurricane formation. In particular, fast-rotating worlds have stronger upper-level winds, and these can disrupt hurricanes. One difference in their method from that of Yan and Yang was that instead of just specifying a fixed sea temperature, they used a more complicated ocean model that allowed the atmosphere and the ocean to heat and cool each other. When they did this, they did not simulate hurricanes on the nightside, unlike Yan and Yang's results.

It is not surprising that hurricanes can form on worlds like these that have big oceans. But such storms might also form on worlds that have little surface water. Building on the 2011 work of NASA's Agnieszka Mrowiec, in 2019 Timothy Cronin of M.I.T. and Dan Chavas of Purdue used a simplified theoretical model to show that tropical cyclones could form even if the surface were dry. The simulated storms are weaker than those that form over oceans, but they are definitely tropical cyclones. The bone-dry surface used in some of their simulations was accompanied by a very dry atmosphere, with near-surface relative humidity of about 0.1%, much less than the lowest humidities typically recorded in desert regions of Earth. One drawback is that the model used in this study is highly idealized and much simpler than a full-blown global climate model. To my knowledge, the ability of a global climate model to generate dry hurricanes (call them "drycanes") has not yet been assessed.

But given the results that have already been produced, one can speculate on the kind of world where drycanes might form. If we stick to planets circling M stars, then warm desert worlds with rotation periods of about ten days would be favored. Meteorologically, these storms would manifest at the planetary surface as ferocious dust storms, driven by the planet's Coriolis effect.

Huh . . . where have we heard before about Coriolis-driven storms on a desert world? On Arrakis, of course.

After Paul Atreides escapes from the Harkonnen invasion of Arrakis, he and his mother Jessica flee in an ornithopter. They then encounter a Coriolis storm, a drastic vortex of sand with winds approaching eight hundred kilometers per hour. This is a lot stronger than the desert hurricanes discussed above. Paul's ornithopter escapes from the storm's grip in a short period of time, suggesting that the Coriolis storm might be a much smaller weather system than a hurricane, more like a tornado or dust devil. These smaller systems cannot be captured by the relatively coarse resolution of the climate modeling studies performed to date. By analogy to the desert regions of Earth, though, there should be plenty of dust devils on Arrakis.

Dust devils occur occasionally on Earth, but they are frequent on Mars. Dust devils are caused by a strong vertical temperature gradient near the ground combined with some initial rotation, either clockwise or anticlockwise. On Mars, the atmosphere is a lot thinner than Earth's, and thus is not able to transport much heat vertically away from the surface. This means that a strongly heated surface and a very cold lower atmosphere can coexist. This very strong vertical gradient of temperature causes dust devils on Mars to be bigger and longer lasting than on Earth. Dust devils on both planets usually do not have destructive winds, although the strongest ones can do some minor damage.

They also sound weird. As luck would have it, in 2021 a microphone on NASA's Perseverance rover captured the sound of a dust devil as it passed directly over the spacecraft. There is a hissing sound as the little storm approaches the rover, then a kind of windy, flapping noise as the dust devil envelops the rover, then more hissing as it passes by—certainly not the roaring of a terrestrial tornado, or even the whooshing of an earthly dust devil. The atmosphere of Mars is thin and does not transmit sound as well as Earth's air does. Also, its carbon dioxide atmosphere suppresses high frequency noise. For example, a dust storm might have lightning and thunder, but the noise would be short-lived, difficult to hear, and would lack high frequencies—it might sound like a grumbly thud.

While hissing dust devils and grumbling dust storms do not have really dangerous winds, tornadoes do. Tornadoes need thunderstorms to form. In a previous article in *Analog* ("Dune and Superdune," November/December 2023), I pointed out that simulations of the climate of Arrakis suggested that there would be some summer precipitation in the mountains near its capital, Arrakeen. One can speculate that this rainfall would most likely be in the form of thunderstorms. If thunderstorms occur, so might tornadoes. It is debatable, though, whether tornadoes on a desert world would really have winds of eight hundred kilometers per hour, like a Coriolis storm on Arrakis. Maximum winds recorded at Earth's surface are those in intense F5 tornadoes, at about three hundred m.p.h. (more than five hundred kilometers per hour). It is unknown whether there would be enough energy in the atmosphere of a warm desert world to support winds considerably stronger than this.

The maximum wind occurring on a planet depends on a number of factors, including available energy, surface friction, and the presence of intense weather systems. It is clear that very strong winds can occur on gas giant planets, because we have already measured them in our own Solar System. But even more extreme winds occur on planets in other stellar systems. An example is the hot Jovian HD 189733 Ab, circling a K star about twenty parsecs away in the constellation Vulpecula. Only slightly bigger and more massive than Jupiter, this planet receives over three hundred times as much stellar radiation as Earth does. As a result, typical dayside temperatures are above 1,400K (more than 2000°F), and the weather is extreme. We know this because this planet is one of the best observed extrasolar planets, as its star is bright and nearby.

This world was discovered in 2005 by the transit method, where a planet periodically passes in front of its star and partially blocks its light. When this happens, starlight can pass through the planet's atmosphere, enabling observations to be made of its atmospheric spectrum. This reveals a lot of information about this strange world. First, its appearance: it is one of the few exoplanets to have its color reliably determined. In 2013, Thomas Evans of Oxford and his team analyzed observations from the Hubble Space Telescope and found that the planet reflects more blue light than red light, concluding that the planet is a deep blue color, probably cobalt blue. Next, it is evaporating: the proximity of its star means that it is slowly losing its atmosphere. It still has plenty of gas left, though. The star has about 15 billion years left before it turns into a red giant, and by that time the planet will have only lost about 0.2% of its current mass.

There is likely some rain in its atmosphere, if molten glass falling from silicate clouds counts as "rain." There are also some hefty breezes. I'm not sure what word one would use to describe hypersonic winds of 8,640 kilometers per hour (5,400 miles per hour). None of our terrestrial terms seem adequate (tempest, hurricane, etc.). And these are not even the strongest planetary winds measured. The ultra-hot Jovian WASP-76 Ab is located 195 parsecs away in the constellation Pisces. It was discovered in 2013 by the Wide Angle Search for Planets (WASP), an international observing program that uses specially designed telescopes to detect planets that transit in front of their stars. WASP-76 Ab has high-hypersonic winds of 19,000 kilometers per hour (about 12,000 miles per hour). These are driven by the enormous differences in incoming stellar radiation from its dayside to its nightside, far exceeding anything found in our Solar System. Incoming radiation on the dayside is about four thousand times the amount received by Earth. This leads to temperatures on the dayside of about 2600K, so hot that clouds are thought to be absent there. From the dayside, winds blast towards the nightside, where the "cooler" conditions enable the condensation of some atmospheric constituents into clouds.

One potential cloud constituent is iron. It could well be gaseous on the dayside but liquid on the nightside, condensing there to form iron clouds. This tempting scenario was recently examined by Olivier Demangeon of the Astrophysics and Space Science Institute of the University of Porto and a long list of collaborators. Previously, astronomers had observed a spike in the light output of WASP-76 Ab just before it was eclipsed by its star, but only on one side of the planet, at the extreme eastern edge (the "limb"). It is proposed that clouds on the eastern limb are causing this spike. While we don't know for sure, it is possible that winds on this planet typically travel from west to east. As these winds pass the eastern limb into the nightside, the atmosphere cools and clouds form. Then as the winds push the clouds around the nightside toward the western limb, the iron rains out, and there is less cloud. Thus there is no spike in reflectivity on the western limb.

Demangeon takes this argument one step further to propose that on the eastern limb, the iron clouds are causing a glory to occur. On Earth, a glory is a halo-like object caused by light passing through clouds and being refracted by water droplets. A similar effect occurs in the northern hemisphere midlatitudes when a warm front is approaching, known as the "ring around the moon," a circular halo caused by moonlight passing through the ice crystals of cirrostratus clouds. Glories are seen in the direction opposite to the Sun as its rays strike the clouds below. They are reasonably common and can be seen from mountain peaks, aircraft, and even the International Space Station. They were also observed in the clouds of Venus by the orbiting Venus Express spacecraft in 2011. On WASP-76 Ab, the lack of a glory at the western limb is explained by relative deficiency of iron droplets there. If this explanation holds up, it would be the first detection of a glory on an extrasolar planet. Naturally, this is a recent result and awaits confirmation by subsequent observations and further analysis. For instance, given that the atmosphere of this planet likely has a number of other constituents beside iron, they might also be playing an important role in cloud formation, challenging the simple hypothesis of iron cloud droplets. Also, our knowledge of the pattern of winds and cloud formation on WASP-76 Ab is rudimentary, to say the least.

I guess it's a matter of opinion whether a particular planet like WASP-76 Ab has the worst weather of any exoplanet so far discovered. Jovian planets like WASP-76 Ab typically have terrible weather and are almost by definition uninhabitable by human beings. Perhaps more intriguing would be the discovery of a marginally habitable terrestrial planet with terrible storms or wild seasonal variations in temperature, but we haven't found one of those yet. There are plenty of such worlds in science fiction, though. From the centuries-long seasons of Helliconia to the worldwide winter of Gethen, science fiction writers have pushed the boundaries of what is possible weatherwise on habitable planets. And then there is always Arrakis.

With all of this talk about how awful the weather is on other worlds, it has been pointed out by others that the surface of our planet is not the only place in our Solar System where we would not have to wear spacesuits. On Venus, at a height of about 55 km above its hellish surface, the temperature is about 27°C (81°F) and the atmospheric pressure is about five hundred mb, or about the pressure on Earth at a height of 15,000 feet. These are perfectly habitable conditions, and in theory all one would need would be a bathing suit, a breathing mask, and a big helium balloon with a basket under it so that one would have somewhere to stand. Of course, there is the slight problem that the surrounding clouds at this altitude are chock-full of sulphuric acid droplets, with very low ph values. Teflon protects against them, but wearing a full-body teflon suit to avoid acid burns seems almost as onerous as wearing a spacesuit. And it would be unwise to fall out of the balloon basket—it would be a long, hot trip to the bottom. Maybe the grumbling dust storms on Mars and the Coriolis storms on Arrakis aren't so bad after all. ■

Further reading:

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Garcia, V., Smith, C.M., Chavas, D.R., and Komacek, T.D., 2024. Tropical cyclones on tidally locked rocky planets: Dependence on rotation period. The Astrophysical Journal, 965(1), 5.

Komacek, T.D., Chavas, D.R., and Abbot, D.S., 2020. Hurricane genesis is favorable on terrestrial exoplanets orbiting late-type M Dwarf stars. The Astrophysical Journal, 898(2), 115.

Yan, M. and Yang, J., 2020. Hurricanes on tidally locked terrestrial planets: Fixed surface temperature experiments. Astronomy & Astrophysics, 643, A37.

The sound of a dust devil on Mars: https://www.smithsonianmag.com/smart-news/listen-to-the-sound-of-a-dust-devil-swirling-around-on-mars-180981285/

Kevin Walsh is a professorial fellow in the School of Geography, Earth and Atmospheric Sciences at the University of Melbourne. He has research interests in tropical meteorology, climate change, and planetary science. His new book is Planets of the Known Galaxy: Fact and Fiction About the Nearest Stars and Their Worlds.