AstroTalk: Behind the news headlines of March–May 2020

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Iron rain and climate change on hot Jupiters

Among the most exciting astronomy news that stood out during the past few months, a lot of news stories highlighted our ever-increasing insights and knowledge about the atmospheres of so-called "hot Jupiters." Hot Jupiters represent a common type of gaseous, giant planet that always orbits close to its host star. How close? Well, we'll get to that!

Now, an international team of researchers, led by astronomers from the University of Amsterdam (Netherlands), has directly demonstrated the presence of iron in the atmosphere of a hot Jupiter for the first time.

The exoplanet, known as KELT-9b, orbits around its host star, KELT-9, in just 36 hours. The star and planet are located at a distance of approximately 620 light-years from Earth in the Cygnus constellation. The star has a temperature of over 10,000 degrees Celsius, which is almost twice as hot as our Sun. KELT-9b is bigger than Jupiter, but it is around thirty times closer to its own host star than Earth is to our Sun.

The researchers already knew that there had to be iron in the planetary atmosphere. A few years ago, they already saw signs of this when studying the starlight while the planet passed in front of its star

In the new observations, the researchers looked directly at the light of the planet. This is complicated, since the planet is outshone by the light of its host star. In addition, because of its proximity to its host star, one year on the planet lasts only about one day and a half. During half of this very short "year," the planet's night-side is facing Earth, but it is too dark to be seen. Thus, the researchers picked up the light during a short period of only 8 hours, just before the planet disappeared behind its star, to observe its hotter, brighter day-side.

Lorenzo Pino, lead author of the study, compares looking for the light from the exoplanet in the glare of its host star with looking at a firefly near a lamp post:

> "*A few years ago we saw the shadow of the firefly, or in our case, the shadow of the exoplanet. We've now looked at the exoplanet directly*."

The researchers made their observations on the Spanish island of La Palma in July 2018 using an Italian telescope, the *Telescopio Nazionale Galileo*. This telescope features HARPS-N, a spectrograph that can split light into the wavelengths it is composed of and reveal the presence of specific atoms and molecules in the planetary atmosphere.

The researchers extracted the emission lines of atoms using a technique called "cross-correlation." Pino compares cross-correlation with Photoshopping a series of film images:

> "*The star is stationary, but the planet is moving. The cross-correlation is a kind of filter that moves with the planet. This allows us to isolate the planetary light*."

Based on the data, the researchers now think that the iron in the atmosphere of exoplanet KELT-9b heats the upper layers of its atmosphere, making it warmer than the lower layers. The idea is that the iron absorbs the starlight, thus heating the atmosphere. On Earth, a similar process takes place in our own atmosphere. However, in our case it is not iron but ozone that heats up the top layers.

Meanwhile, another team of researchers using the European Southern Observatory's (ESO) *Very Large Telescope* (VLT) have observed an extreme hot Jupiter, WASP-76b, where they suspect it actually rains iron. WASP-76b is located some 640 light-years away in the constellation of Pisces. The ultra-hot giant exoplanet has a day-side where temperatures climb above 2400 degrees Celsius, high enough to vaporise metals. Strong winds carry iron vapour to the cooler night-side where it condenses into iron droplets.

> "*One could say that this planet gets rainy in the evening, except it rains iron*," says David Ehrenreich from the University of Geneva (Switzerland). He led a study, published in the journal *Nature*, of this exotic exoplanet.

This strange phenomenon happens because the "iron rain" planet only ever shows one face, its day-side, to its parent star, with its cooler night-side remaining in perpetual darkness. Like our Moon on its orbit around the Earth, WASP-76b is "tidally locked:" it takes as long to rotate around its rotation axis as it does to orbit around the star.

On its day-side, it receives thousands of times more radiation from its host star than the Earth does from the Sun. It's so hot that molecules separate into atoms, and metals like iron evaporate into the atmosphere. The extreme temperature difference between the day- and night-sides results in vigorous winds that bring the iron vapour from the ultra-hot day-side to the cooler night-side, where temperatures decrease to around 1500 degrees Celsius.

Not only does WASP-76b have different day–night temperatures, it also has distinct day–night chemistry (that is, it has different atoms and molecules in its day–night atmosphere), according to the new study. Using the new *ESPRESSO* instrument on the VLT in the Chilean Atacama Desert, the astronomers identified for the first time chemical variations on an ultra-hot Jupiter. They detected a strong signature of iron vapour at the evening boundary that separates the planet's day-side from its night-side.

> “*Surprisingly, however, we do not see the iron vapour in the morning*,” says Ehrenreich. The reason, he says, is that “*it is raining iron on the night-side of this extreme exoplanet*.”

> “*The observations show that iron vapour is abundant in the atmosphere of the hot day-side of WASP-76b*,” adds María Rosa Zapatero Osorio, an astrophysicist at the Centre for Astrobiology in Madrid (Spain) and lead of the *ESPRESSO* science team. “*A fraction of this iron is injected into the night-side owing to the planet’s rotation and atmospheric winds. There, the iron encounters much cooler environments, condenses and rains down*.”

ESPRESSO—the Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations—was originally designed to hunt for Earth-like planets orbiting around Sun-like stars. However, it has proven to be much more versatile.

> “*We soon realised that the remarkable collecting power of the VLT and the extreme stability of ESPRESSO made it a prime machine to study exoplanet atmospheres*,” says Pedro Figueira, *ESPRESSO* instrument scientist at ESO in Chile.

> “*What we have now is a whole new way to trace the climate of the most extreme exoplanets*,” concludes Ehrenreich.

But this is not all… Yet more atmospheric insights of hot Jupiters were obtained in the last few months, in particular of the giant, super-hot Jupiter planet WASP-79b. Scientists say that its weather forecast is steamy humidity, scattered clouds, iron rain and yellow skies.

The team, based at Johns Hopkins University (USA), combined observations obtained with the *Hubble Space Telescope* with data from the Magellan II telescope in Chile to analyse the atmosphere of this hot Jupiter. It orbits a star that is hotter and brighter than our Sun, and which is located at a distance of 780 light-years from Earth in the constellation Eridanus. Among exoplanets, WASP-79b is among the largest ever observed.

The surprise in recently published results, is that the planet’s sky doesn’t show any evidence for an atmospheric phenomenon called “Rayleigh scattering,” where certain colours of light are dispersed by very fine dust particles in the upper atmosphere. Rayleigh scattering is what makes the Earth’s skies blue by scattering the shorter (bluer) wavelengths of sunlight.

Because WASP-79b doesn’t seem to have this phenomenon, the daytime sky would likely be more yellow, researchers say.

> “*This is a strong indication of an unknown atmospheric process that we’re just not accounting for in our physical understanding. I’ve shown the WASP-79b spectrum to a number of colleagues, and their consensus is* ‘that’s weird,’” said Kristin Showalter Sotzen.

The team would like to find other planets with similar conditions to learn more.

> "*Because this is the first time we've seen this, we're really not sure what the cause is*," Sotzen said. "*We need to keep an eye out for other planets like this because it could be indicative of unknown atmospheric processes that we don't currently understand. Because we only have one planet as an example we don't know if it's an atmospheric phenomenon linked to the evolution of the planet*."

Hot Jupiters orbit so close to their stars that the conventional wisdom is that they migrated inwards towards a tight orbit around their host star, after bulking up on cold gas in the frigid outer reaches of a planetary system. WASP-79b completes an orbit in just 3½ days. But this planet is in an unusual polar orbit about the star, which goes against scientists' theories about how planets form—especially for hot Jupiters.

The new results might potentially give additional clues to the history of similar planets. Some hot Jupiters appear to have hazy or cloudy atmospheres while others appear to have clear atmospheres. If it's like other hot Jupiters, WASP-79b may have scattered clouds, and iron lifted to high altitudes could precipitate as rain, just as we think is happening on WASP-76b.

WASP-79b is twice the mass of Jupiter and it is so hot that it has an extended atmosphere, which is ideal for studying starlight that is filtered through and grazes the atmosphere on its way towards Earth.

To study the planet, the team used a spectrograph on the Magellan II telescope at Las Campanas Observatory in Chile. They expected to see a decrease in the amount of blue starlight because of Rayleigh scattering. Instead, they saw the opposite trend. The shorter, bluer wavelengths of light appear to be more transparent, indicating less absorption and scattering by the atmosphere.

WASP-79b was also observed as part of the *Hubble Space Telescope*'s Panchromatic Comparative Exoplanet Treasury (PanCET) programme, and those observations showed that there is water vapour in the planet's atmosphere. Therefore, the giant planet was selected as an "Early Release Science" target for the upcoming *James Webb Space Telescope*. The *Webb Telescope* is expected to provide much more spectral data over longer infrared wavelengths. These observations may reveal more evidence for water vapour in the planet's atmosphere and will provide a detailed view of its chemical makeup.

Indeed, understanding the atmospheres of giant exoplanets, including hot Jupiters, is becoming "big business" in astronomy.

After examining a dozen types of stars and a roster of planet surfaces, Cornell University astronomers have developed a practical model—an environmental colour "decoder"—to tease out climate clues for potentially habitable exoplanets in distant galaxies.

> “*We looked at how different planetary surfaces in the habitable zones of distant solar systems could affect the climate on exoplanets*,” said Jack Madden. “*Reflected* light *on the surface of planets plays a significant role not only on the overall climate, but also on the detectable spectra of Earth-like planets*.”

The research team combined details of a planet’s observable surface colour and the light from its host star to calculate a “climate.” For instance, a rocky, black basalt planet absorbs light well and would be very hot, but add sand or clouds and the planet cools down. And a planet with vegetation and orbiting a reddish “K-type” star (which is somewhat cooler than our Sun) will likely have cool temperatures because of how those surfaces reflect its star’s light.

> “*Think about wearing a dark shirt on a hot summer day. You’re going to heat up more, because the dark shirt is not reflecting light. It has a low* albedo *(it absorbs light) and it retains heat*,” Madden said. “*If you wear a light colour, such as white, its high albedo reflects the light—and your shirt keeps you cool. It’s the same with stars and* planets.”

> “*Depending on the kind of star and the exoplanet’s primary colour—or the reflecting albedo—the planet’s colour can mitigate some of the energy given off by the star*,” senior co-author Lisa Kaltenegger said. “*What makes up the surface of an exoplanet, how many clouds surround the planet, and the colour of the host star can change an exoplanet’s climate significantly*.”

Madden said forthcoming facilities like the *Extremely Large Telescope* will allow scientists to gather data so as to test a large variety of climate predictions.

> “*There’s an important interaction between the colour of a surface and the light hitting it*,” he said. “*The effects we found based on a planet’s surface properties can help in the search for life*.”

Now that would be exciting!

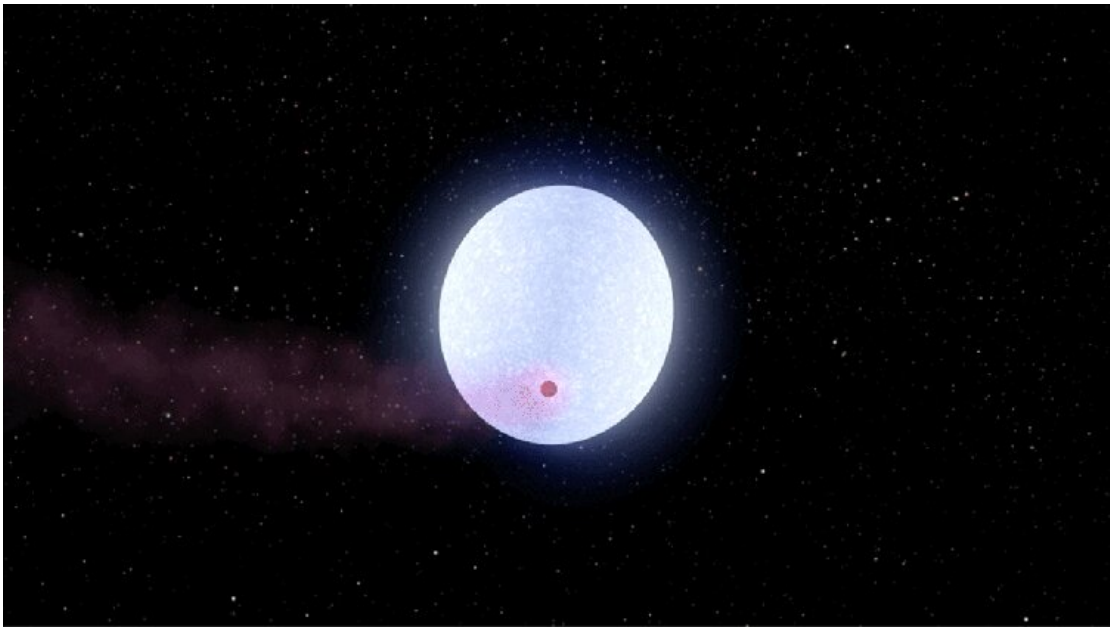

Figure 1: Artistic impression of exoplanet KELT-9b orbiting its star KELT-9. (*Credit: NASA/JPL-Caltech*)

Figure 2: This illustration shows a night-side view of the exoplanet WASP-76b. To the left of the image, we see the evening boundary of the exoplanet, where it transitions from day to night. (*Credit: ESO/M. Kornmesser*)

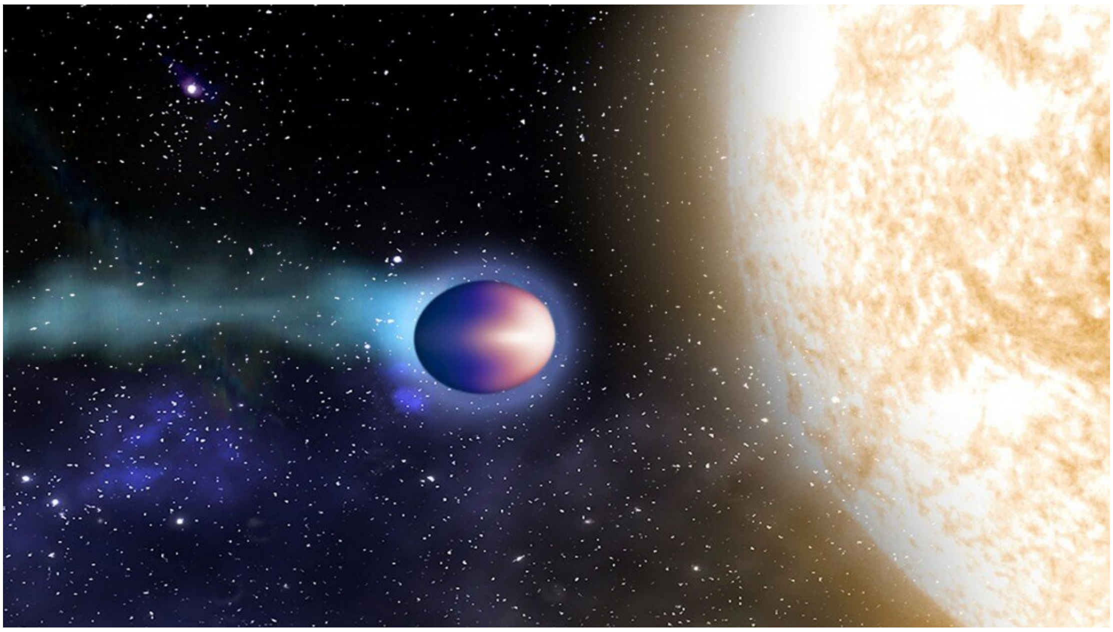

Figure 3: Atmospheric gases recede from a "hot Jupiter," which is a Jupiter-size, egg-shaped planet that orbits close to its host star, in this artistic rendering. (*Credit: Matthew Fondeur*)

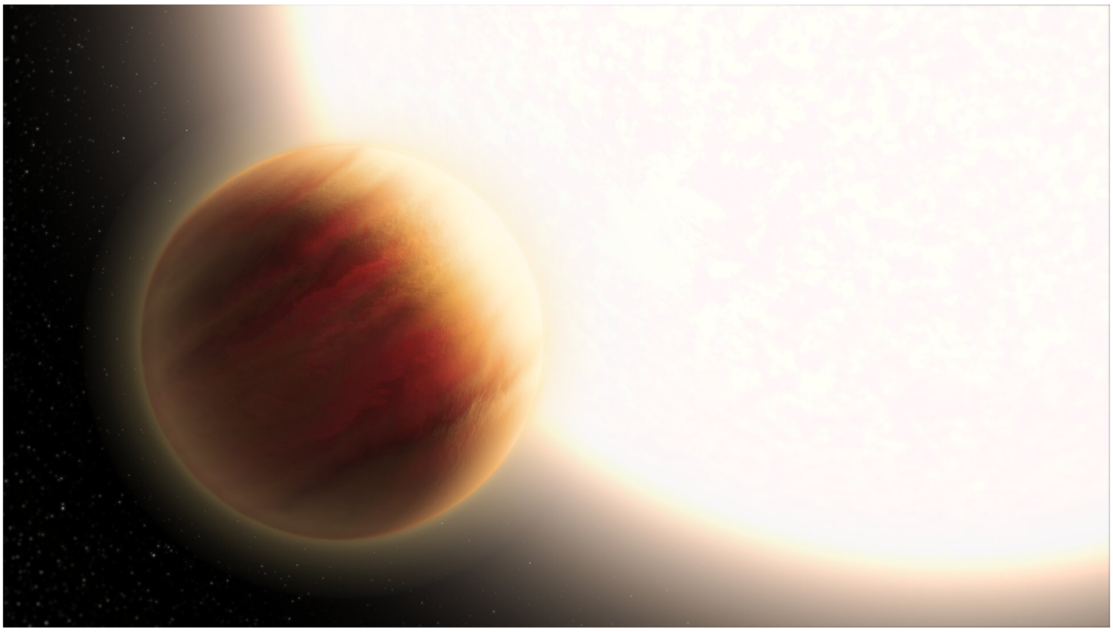

Figure 4: Artist's illustration of the super-hot exoplanet WASP-79b. (*Credit: NASA, ESA, and L. Hustak/STScI*)

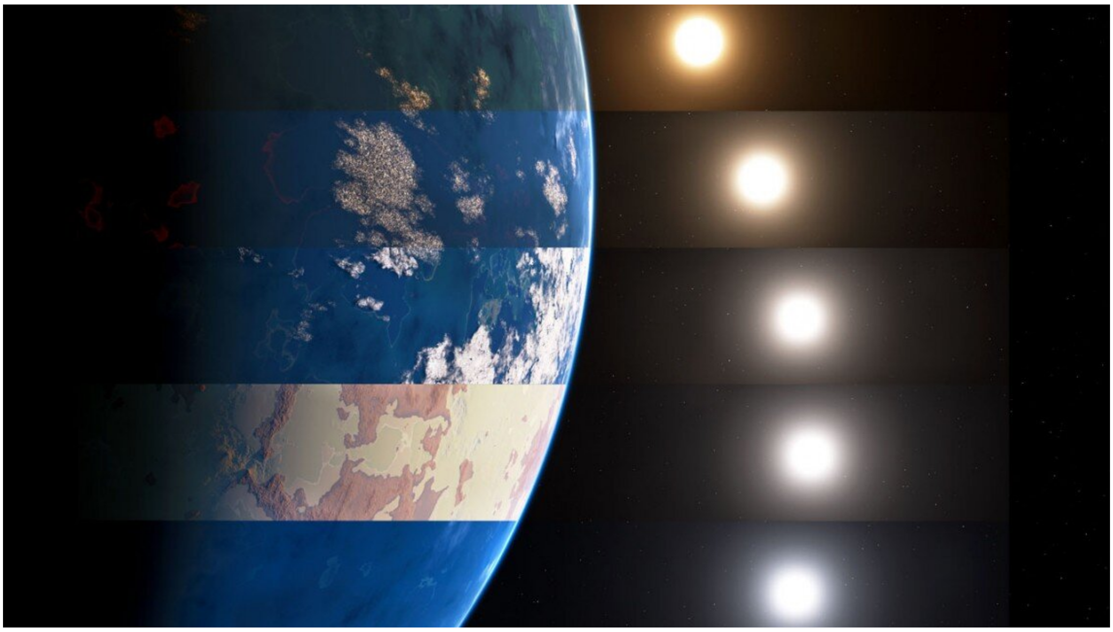

Figure 5: In this artistic rendering, different kinds of stars are shown as they interact with various Earth-like surfaces in distant solar systems. The combinations create an array of climates. Thus, in the search for exoplanets, astronomers can be guided by colour for possible habitable planets. (*Credit: Jack Madden*)

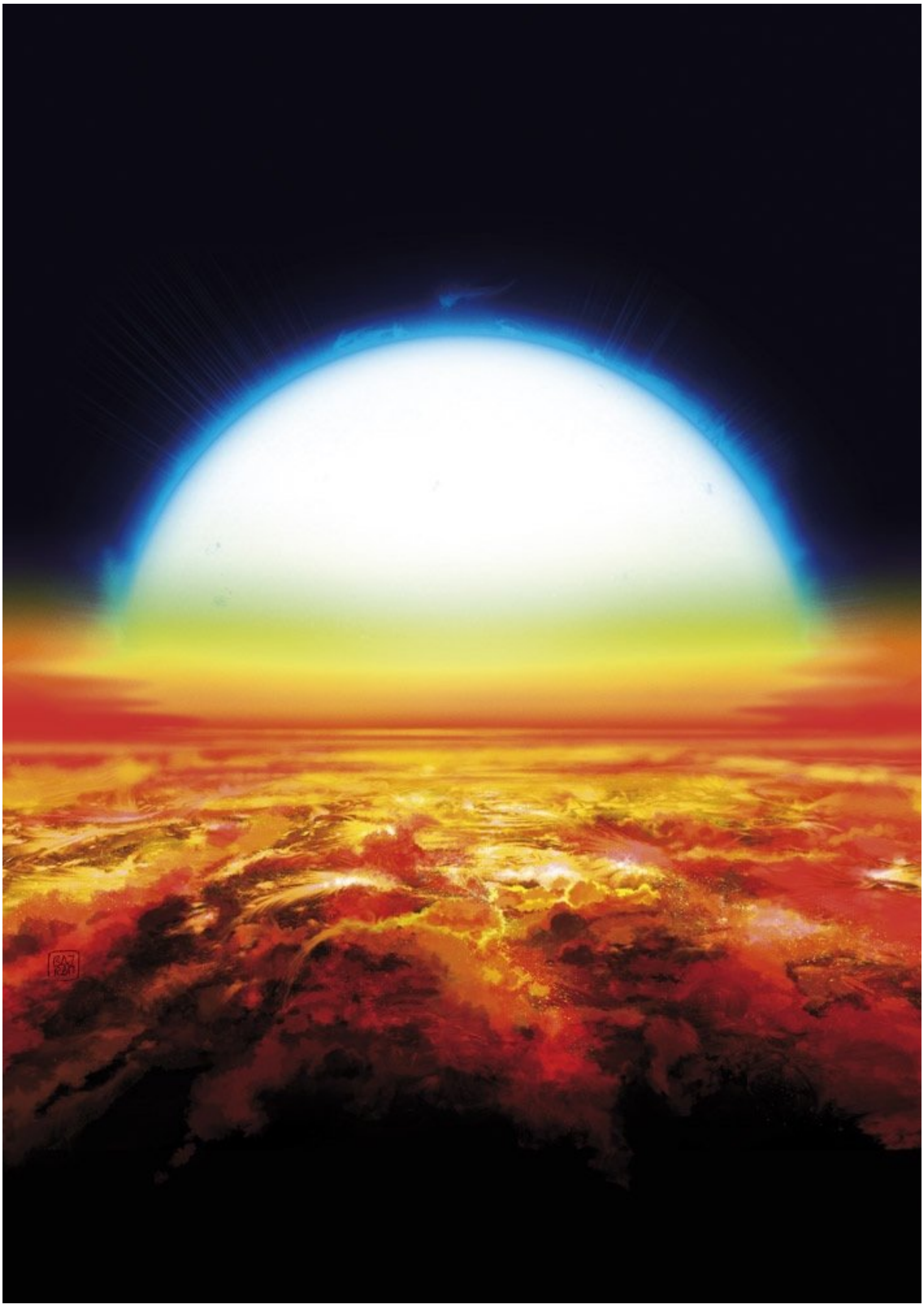

Figure 6: Artist's view of a sunset over KELT-9b. The nearby warm blue star covers 35° in the planet's sky, about 70 times the apparent size of our Sun in the Earth's sky. Under this scorching sun, the planet's atmosphere is warm enough to shine in reddish-orange tones and vaporise heavy metals such as iron and titanium. (*Credit: Denis Bajram*)

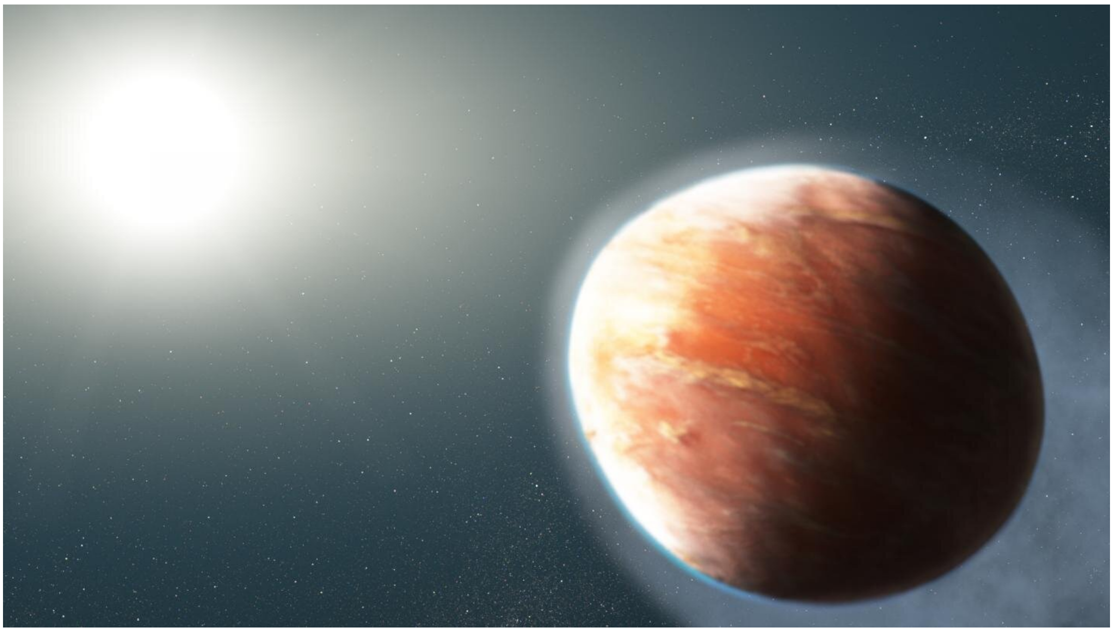

Figure 7: This artist's illustration shows WASP-121b, a distant world that is losing magnesium and iron gas from its atmosphere. WASP-121b's orbit is so close that the star's gravity is nearly ripping the planet apart, giving the planet an oblique football shape. (*Credit: NASA, ESA, and J. Olmsted/STScI*)