Pushing the characterization of exoplanet atmospheres down to temperate rocky planets in the era of JWST

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ENGLISH SUMMARY

"Where Do We Come From? What Are We? Where Are We Going?" The study of planets inside and outside of our solar system is integral to answering these fundamental questions of humanity. Astronomy as a whole is shedding light on the diversity of the cosmos and our place in it. In my field of research, we do this by characterizing planets outside our solar system, so-called exoplanets. By learning about their formation, evolution, composition, and habitability, we ultimately learn about our origins, the future of our own planet, and its uniqueness. The holy grail of exoplanet research is ultimately to determine whether the Earth and life as we know it are rare or ubiquitous. Scientists will argue when we will finally find an "Earth-twin" that could host life as we know it, but we have surely never been that close to reaching this goal.

It is remarkable how much we have learned about these distant worlds in just a few decades: Since the first discovery of exoplanets in the 1990s, we know of more than 5,500 planets at the moment. Ground and space-based telescopes and instruments were built to discover these planets. Typically, however, we cannot see the exoplanet directly. They are too close to their host stars, which are orders of magnitude brighter. Therefore, it is still a challenge to spatially resolve planets around their stars. More often, we observe the combined light from both sources — the star and the planet — which can provide us with a whole range of planetary properties, from fundamental ones like their size and mass up to characteristics like their atmospheric composition, their heat redistribution, or their reflectivity. NASA launched space missions, such as the Kepler Space Telescope in 2009 and the Transiting Exoplanet Survey Satellite (TESS) in 2018, to discover these distant worlds and measure their sizes. These telescopes utilized a technique called the "transit method," which relies on the system architecture to be edge-on, so that the planet would occult — or "transit" — their host star periodically. During such a transit, the exoplanet covers the stellar disk as seen from the Earth, leading to an observed decrease in flux. This method has been the most successful one up to now, caused by the simple scalability of the problem: one just has to point a sensitive telescope up to the sky and record the brightness of stars in the field of view over time to discover new planets. A different technique called the radial velocity method can then provide us with the planetary masses. From the measured radii and masses, we derive the planet's bulk density, which informs us about its composition: A planet with a big iron core will have a higher density than one that is dominated by silicates with a small core. The majority of rocky exoplanets are Earth-like in composition, meaning around 30% iron and 70% "rocks" or silicates. Planets bigger than 1.6 times the Earth's radius are expected to have retained a hydrogen atmosphere with a significant amount of their mass in gas form. These planets are also expected to have molten surfaces, as the pressure strongly increases with decreasing altitude. Once you reach the surface, the temperature will be too high to host a solid, unmolten surface. This is typically why we do not consider these bigger worlds to be rocky.

However, despite measuring the densities of rocky planets and learning about their bulk compositions, we still do not know much about the composition of small planet atmospheres and how often these worlds hold onto them. The "Great Observatories," which were launched by NASA between 1990 and 2003, included two space telescopes that would ultimately become the workhorse facilities for the characterization of transiting exoplanets over the last decade: The Hubble Space Telescope was launched in 1990 aboard Space Shuttle Discovery with an aperture of 2.4 meters, and the Spitzer Space Telescope in 2003 with an 85 cm mirror. In space, telescopes avoid contamination by the thermal infrared background of the Earth, which makes precise infrared observations possible. Although both telescopes were never designed to study exoplanets, clever data processing routines and, in the case of Hubble, upgrades during the Hubble servicing missions led to the atmospheric characterization of many Jupiter-sized and also smaller exoplanets.

After the Spitzer Space Telescope was shut off in January 2020, the exoplanet community lost the capability to observe exoplanets in transmission or emission in the infrared at wavelengths greater than 2 microns from space. This was a big loss, as molecules we are interested in finding in the atmosphere of other planets, such as water (H_2O) or carbon dioxide (CO_2), have features in the infrared. The strong absorption of carbon dioxide was noted by the astrophysicist and science communicator Carl Sagan, when he testified before Congress in 1985 on climate change. The following is a direct quote from Carl Sagan when he addressed the Congress members during the hearing:

> "The air between us is transparent, except in Los Angeles and places of that sort. In the ordinary visible part of the spectrum, we can see each other. But if our eyes were sensitive at, say, 15 microns in the infrared, we could not see each other. The air would be black between us. And that's because, in this case, carbon dioxide. Carbon dioxide is very strongly absorbing at 15 microns. And other wavelengths in the infrared. Likewise, there are parts of the infrared spectrum where water vapor absorbs, where we could not see each other if we were only as far apart as we are in this room."

The search for atmospheres on rocky exoplanets containing molecules like water, carbon dioxide, or oxygen requires a precise infrared telescope. Thankfully, after many delays, JWST was launched on Christmas Day 2021, providing scientists again with the capability to study planets in these infrared wavelengths with unprecedented precision. Its groundbreaking precision is due to many factors, like a large collecting area of 6.5 meters and the thermal stability of the telescope. JWST therefore gives us for the first time the possibility to search for high-mean-molecular-weight atmospheres made of carbon dioxide (CO_2), oxygen (O_2), and nitrogen (N_2) on temperate rocky worlds.

There are generally two techniques to study the atmospheres of transiting exoplanets. The first one, occurs during a transit and is therefore called transmission spectroscopy: when a planet occults its host star from our view as the observer, a part of the starlight will travel through the atmosphere of the planet, if there is any. Certain wavelengths will be absorbed by the constituents of the atmosphere. These missing wavelengths are then observed by us, and we can deduce the elements and molecules that make up the gas shell around the planet. The other method to characterize the atmospheres of exoplanets occurs approximately half an orbit after the transit when the planet disappears behind its host star; we call that an "eclipse." During the eclipse itself, we only observe the stellar light. Any flux emitted by the planet is hidden by the star. However, right before and after the planet hides behind its star, we observe the emission coming from the dayside of the planet. From this peek-a-boo game with the planet, we measure an emission spectrum — the method is therefore called emission spectroscopy — and we can detect elements or molecules in the atmosphere of the planet or directly study its surface. When we study the emission coming from not only the dayside of the planet but from the other sides of the planet during the orbit of the planet around its host star, we observe a so-called phase curve. These kinds of observations can then inform us about global processes like heat transport due to winds in the planet's atmosphere.

K2 and Spitzer phase curves of the rocky ultra-short-period planet K2-141 b hint at a tenuous rock vapor atmosphere

In Chapter 2, we observed such a phase curve for a lava exoplanet called K2-141 b using Spitzer. These lava planets are characterized by their really short orbital periods and very hot daysides. With an orbital period of just 7 hours, the planet is so strongly irritated by its star that the average dayside temperature is above 2000 Kelvin. That is enough to melt the rocks on the planet's surface, leading to a dayside magma ocean, and potentially to a thin rock vapor atmosphere caused by the evaporation of rocks. The latter is especially interesting, as the study of the evaporated atmosphere might eventually tell us about the composition of the planet's surface. In my work, I combined previously taken Kepler observations of K2-141 b with new Spitzer data. The Spitzer Space Telescope stared at the star for about 70 hours, leading to the observation of 10 continuous orbits of the planet. Combining the data taken by Kepler in the optical with the Spitzer infrared observations, we tentatively attribute the deep eclipse observed by Kepler to such a rock vapor atmosphere. However, only follow-up will reveal the true nature of the planet. Thankfully, JWST observations of the planet were already taken, and the interpretation is currently underway. Due to its wavelength coverage and precision, JWST will improve our understanding of lava planet atmospheres.

PACMAN: A pipeline to reduce and analyze Hubble Wide Field Camera 3 IR Grism data

In Chapter 3, I present a publicly available tool for astronomers to access and process exoplanet observations taken by one of the instruments on the Hubble Space

Telescope. The original code has been used in many publications over the past decade and is now made available for everyone under the name PACMAN. Hubble's Wide Field Camera 3 (WFC3) instrument was installed during a servicing mission in 2009. The spectral range of WFC3 notably picks up molecular infrared absorption from water, which allowed for the successful detection of water in the atmospheres of over a dozen exoplanets. However, analyzing Hubble data presents challenges, with different pipelines producing conflicting results in the literature in the past. To ensure research reproducibility, it's good scientific practice for the software used in data reduction and analysis to be open-source. This approach makes it easier to compare different pipelines and lowers the barriers for newcomers entering the field of exoplanet atmospheres. The source code of PACMAN and examples on how to use the code to get a transmission or emission spectrum of an exoplanet can therefore be found online.

No thick carbon dioxide atmosphere on the rocky exoplanet TRAPPIST-1 c
In Chapter 4, we published one of the first results of JWST, shedding light on a rocky exoplanet and offering insights into its atmospheric makeup. Over the past decades, our understanding of exoplanets has expanded significantly, revealing that small planets are quite common throughout the Milky Way. It's estimated that around 20 to 50% of stars may host a planet similar in size to Earth. By measuring the densities of these exoplanets, we infer that they typically possess a rocky composition similar to our own planet. However, our knowledge regarding the atmospheric composition of these terrestrial planets remains limited, and we're still uncertain how often rocky planets hold onto their atmospheres. Thanks to the capabilities of JWST, we now have the capability to search for more Earth-like atmospheres composed of molecules such as carbon dioxide, oxygen, and nitrogen. Of particular interest for astronomers is a system called TRAPPIST-1. This nearby, small star hosts seven transiting terrestrial planets, offering possibilities for studying small planets with a whole range of temperatures. Among these planets, three orbit in the region around the star where the temperatures might be suited for liquid water on the planet's surface, known as the habitable zone. Because of the star's proximity, small size, and relatively low temperature, the planets are ideal candidates for atmospheric follow-up characterization. This provides us with a unique opportunity to search for atmospheres on small planets outside the Solar System. It's worth noting that small stars like TRAPPIST-1 are the most common type of stars in the Milky Way. Hence, finding out if planets orbiting small stars can retain their atmospheres is currently one of the main open questions in the field of exoplanets. If we find that planets orbiting these stars indeed retained substantial atmospheres throughout their existence, then this would offer hopeful indications for the potential habitability of the numerous rocky planets hosted by small stars. But if we find that planets around small stars are devoid of atmospheres, it might suggest that stars similar to the Sun offer a more favorable environment for the emergence of life. To make a step forward in solving these open questions, we observed four eclipses of the exoplanet TRAPPIST-1 c with the Mid-Infrared Instrument (MIRI) aboard JWST. In our observations, we leveraged the strong absorption of CO_2 at 15 microns (as noted in the quote by Carl Sagan

above) to search for an atmosphere on TRAPPIST-1 c. We do not detect a strong absorption caused by CO_2, leading us to exclude certain atmospheric scenarios, particularly those that are dominated by CO_2. Instead, our findings are more consistent with thinner atmospheres or bare-rock surfaces. For instance, we can confidently rule out an atmosphere on TRAPPIST-1 c, which resembles that of a badly ventilated room, i.e., CO_2 concentrations of 1000 ppm at sea level. Interestingly, TRAPPIST-1 c, which lies outside of the star's habitable zone, is similar in size, mass, and irradiation to Venus. One of the main scientific discoveries of this chapter is that, unlike Venus, the planet lacks a high-pressure atmosphere that is primarily made of carbon dioxide. This is the first study to characterize an exoplanet that resembles Venus or is reasonably comparable to Earth. Its findings will help understand the origin and evolution of rocky planets orbiting small stars, thereby guiding future studies of these systems.

A Hubble WFC3 infrared look at the transmission spectrum of the hot, inflated sub-Saturn KELT-11 b

In Chapter 5, we utilize the open-source pipeline PACMAN presented in Chapter 3 to analyze Hubble observations of a hot Jupiter exoplanet KELT-11b and learn about its atmospheric properties. Thanks to the planet's short orbital period and high equilibrium temperature, it's a great target for atmospheric studies. We looked at the stellar light as the planet passed in front of its star and analyzed how it changed as a function of wavelength and time. We found that a commonly used method to analyze the spectra of transiting exoplanets taken by Hubble might not always be accurate. Our observed planetary transmission spectrum also hinted at potential contamination from the star itself. Surface features on the star, such as stellar spots, can influence the spectrum — a phenomenon commonly observed in smaller, cooler stars but less expected in larger stars like our Sun. Our study underscores the importance of robust data reduction and a thorough interpretation of the planetary transmission spectrum, even for high signal-to-noise targets like hot Jupiters. Failure to consider contamination from the host star could lead to misinterpretations, attributing atmospheric features to the planet that actually originate from molecules in the stellar atmosphere.

The β Pictoris b Hill Sphere Transit Campaign - II. Searching for the signatures of the β Pictoris exoplanets through time delay analysis of the δ Scuti pulsations

Finally, in Chapter 6, we study a nearby planetary system called β Pictoris. The system stands out as the closest stellar system where we've directly spotted gas giant planets, along with an intriguing edge-on circumstellar disk and signs of transiting exocomets. We investigated the stellar pulsations of the star in order to see the signatures of the known planets, β Pictoris b and c, and also search for still unknown companions. A star and its planets are always orbiting a common center of mass, which leads to a small periodic change in distance between us and the host star. By measuring the arrival time of the stellar pulsations, we could detect periodic early or late arrivals, hinting at companions, which change the light travel time of the signals. We analyzed photometric data from various ground- and space-based observatories to study the pulsations' stability. We did not detect the signals for the planets due to the high noise in the data. Our analysis also suggests that the star's pulsations themselves drift over time, making it challenging to detect exoplanets through pulsation timing for stars like β Pictoris. While we couldn't see the signatures of the planets using this method, our study sheds light on the limitations and potential of pulsation timing in exoplanet detection.

Previous observations of rocky exoplanets with the Hubble Space Telescope or the Spitzer Space Telescope were primarily able to rule out hydrogen-dominated atmospheric compositions. However, thanks to the remarkable capabilities of JWST, we now have the opportunity to explore more realistic, Earth-like atmospheres on temperate rocky worlds. The frequency and conditions under which these small worlds maintain atmospheres remain uncertain. If we discover that planets orbiting small stars are devoid of atmospheres, it may suggest that Sun-like stars offer a more favorable environment for life to emerge. In any case, the forthcoming discoveries with JWST will mark a crucial milestone in our understanding of the atmospheres, surfaces, and potential habitability of rocky planets. While detecting biosignatures on observable exoplanets with JWST may require quite some luck and observational time, the prospects look promising in the coming decades with the advent of the ELTs and potential future missions like the Habitable Worlds Observatory (HWO) and ESA's Large Interferometer For Exoplanets (LIFE) mission. Ultimately, the most robust method to determine whether a terrestrial exoplanet harbors an atmosphere is to study its thermal emission, reflected light, or transmission spectrum. So let's aim our observatories at rocky planets and embark on this journey of discovery!