Atmospheric dynamics of a near tidally locked Earth-sized planet

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The discovery and characterization of Earth-sized planets that are in, or near, a tidally locked state are of crucial importance to understanding terrestrial planet evolution. For this purpose Venus is a clear analogue. Exoplanetary science lies at the threshold of characterizing hundreds of terrestrial planetary atmospheres, thereby providing a statistical sample far greater than the limited inventory of terrestrial planetary atmospheres within the Solar System. However, the model-based approach for characterizing exoplanet atmospheres relies on Solar System data, resulting in our limited inventory being both foundational and critical atmospheric laboratories. Present terrestrial exoplanet demographics are heavily biased toward short-period planets, many of which are expected to be tidally locked, and also potentially runaway greenhouse candidates, similar to Venus. Here we describe the rise in the terrestrial exoplanet population and the study of tidal locking in climate simulations. These exoplanet studies are placed within the context of Venus, a local example of an Earth-sized, asynchronous rotator that is near the tidal locking limit. We describe the recent lessons learned regarding the dynamics of the Venusian atmosphere and how these lessons pertain to the evolution of our sibling planet. We discuss their implications for exoplanet atmospheres, and outline the need for a full characterization of the Venusian climate to achieve a full and robust interpretation of terrestrial planetary atmospheres.

Exoplanetary science has undergone rapid expansion over the past three decades. As observational techniques have improved, the sensitivity limits have allowed the detection of increasingly smaller exoplanets. The ‘deep dive’ into the terrestrial regime of exoplanet detection was largely enabled by the Kepler mission, a legacy that is now being continued with the Transiting Exoplanet Survey Satellite (TESS). Moreover, these discoveries have revealed the diversity of planetary system architectures, including compact systems of planets close to the host star. The proximity of exoplanets to their host star has spurred further study into tidal locking scenarios, including the timescales and implications for the planets. As such, the local analogues to tidally locked terrestrial planets are exceptionally valuable subjects of examination, as they provide the means to study the pathway to tidal locking and the influence on their atmospheric evolution.

A particular area of focus has been the investigation of those planets that reside within their star’s habitable zone (HZ), defined as the region around a star where a planet may have surface liquid water provided sufficient atmospheric pressure. Many HZ planets have been detected, including several hundred from the Kepler mission. In parallel, the development of climate models and their application to exoplanets have seen a similar rise in activity. These climate simulations are often constructed from parent Earth-based models, and require a substantial number of assumptions regarding intrinsic planetary properties. Furthermore, the effect of tidal locking on potential surface habitability is unresolved, and may accelerate or decelerate the transition of terrestrial planet atmospheres into a runaway greenhouse state. It is expected that exoplanet atmospheric compositional data will provide additional insights that may substantially aid the climate modelling approach. Importantly, the detailed inference of planetary surface conditions relies upon a complete understanding of the limited inventory of terrestrial atmospheres within the Solar System, for which in situ data form the basis of atmospheric models.

The nearest Earth-sized planet is Venus, whose complicated atmosphere remains an enigma in many respects. The surface conditions are among the most extreme observed in the Solar System, with an atmospheric mass two orders of magnitude larger than that of Earth, creating a surface pressure that renders its CO$_2$-dominated atmosphere in a supercritical fluid state. Diagnosing the evolution of Venus from formation to its present state is fundamental to understanding the divergence of Venus and Earth and possible similar evolutionary pathways for exoplanets. Venus is considered an asynchronous rotator, whose present rotational state is probably the result of complex interactions between solar and atmospheric tides. Similarly, the dynamics and super-rotation of the Venusian atmosphere are a consequence of the combined effects of relatively high incident flux, slow rotation, atmospheric structure and interaction with the surface topography. The particular relevance to exoplanets that lie near the tidal locking threshold, for which Venus will always be our best-studied example, is acute.

The terrestrial exoplanet population

The currently known exoplanet inventory consists of a population number that lies in the thousands, from which the diversity of system architectures begins to emerge. Shown in Fig. 1 are histograms of the exoplanet radius distribution for discoveries up until 2012, 2015 and 2021. The data were extracted from the National Aeronautics and Space Administration (NASA) Exoplanet Archive and are current as of 2021 June 10. The green shaded region indicates which planets may be terrestrial, accounting for uncertainties in the radius measurements. The figure demonstrates the marked rise in terrestrial planet detection that occurred between 2012 and 2021, largely due to the results from the Kepler mission. Figure 1 also shows the gradual appearance of a gap in the radius distribution, referred to as the ‘Fulton gap’ or ‘photoevaporation valley’. This radius gap has been suggested to be the result of photoevaporation, suggesting that short-period superEarths may primarily...
Climates of tidally locked worlds

As described in The terrestrial exoplanet population, a significant fraction of the known terrestrial exoplanet population is expected to be near or in a tidally locked state. Consequently, significant effort has been expended toward adapting climate models to slow rotational states, including synchronized rotation. Functionally, this is generally achieved by setting the rotation period to a value similar to the orbital period, and adjusting the spectral energy distribution received at the top of the atmosphere. The application of these simulations has been successfully demonstrated on numerous occasions, some with far-reaching consequences. For example, climate simulations of tidally locked planets have revealed conditions that lead to climate instability, whereby positive or negative feedback results in a runaway climate shift, and potential atmospheric collapse, whereby cooling and condensation of the atmosphere result in marked changes in atmospheric conditions. Others have studied the relationship between atmospheric circulation, convection and thermal structure that tidal locking produces. The HZ boundaries, particularly the inner edge, have been found to have a strong rotational dependence, emphasizing the importance of tidal locking for target selection of potentially habitable worlds. Additional simulations have shown the effects of water trapping and specific cloud features on the dayside of tidally locked planets. Climate simulations have also demonstrated the dependence of the climate dynamics of tidally locked planets on surface topography, discussed further in Venus atmospheric dynamics.

Climate simulations so far have been applied to numerous known exoplanets suspected of being in a tidally locked state, including the nearest exoplanet: Proxima Centauri b. An example of such simulations is the case of Kepler-1649b, a short-period planet orbiting an M dwarf star that is a strong candidate as an exo-Venus analogue. Various simulations of the climate evolution using the general circulation model ROCKE-3D found that, in all cases, the surface temperature quickly rises to the limit of the radiation tables utilized, indicating a progression into a moist or runaway greenhouse state. Shown in Fig. 3 is an example output from these simulations in the form of a Robinson projection of the final surface temperature map with a Venus topography overlay. The initial conditions in this case included an incident flux of twice the solar constant, CO₂ and CH₄ atmospheric compositions of 400 and 1 ppmv (parts per million volume), respectively, and a palaeo-Venus topography with all ocean grid cells set to 1,360 m in depth. Before reaching the limit of the radiation tables, the surface temperature reached a maximum value of 270°C, with a global mean of 112°C. Similar simulations have been used to suggest that Venus may have experienced a significant period of temperate surface conditions, with substantial cloud feedback near the substellar point producing a cooling effect. Such scenarios assume that water inventory in the atmosphere was able to condense at the surface to form oceans, which may have been prevented via early magma oceans and/or insolation flux. Regardless, the atmospheric dynamics of a nearby, slowly rotating, Earth-sized planet, and how it has evolved through time, are a critically important laboratory to test many of these principles.
Venus atmospheric dynamics

Despite a slow rotation, Venus maintains an extremely dynamic climate. The Venusian surface conditions are very different from those found on Earth, with a mean surface temperature and pressure of ~735 K and 93 bar, respectively. Although these surface conditions are globally consistent, the dayside and nightside temperatures

Fig. 2 | The HZ boundaries and tidal locking distance as a function of stellar effective temperature and stellar flux received by the planet. Solid and dotted lines, HZ boundaries; grey dashed line, tidal locking distance. Solar System planets and numerous known exoplanets are included. Figure reproduced with permission from ref. 47, AAS.

Fig. 3 | A Robinson projection of the results from a ROCKE-3D simulation for the exoVenus candidate Kepler-1649b, showing the surface temperature and a Venus topography overlay. The surface temperature reached a maximum of 270 °C and a global mean of 112 °C at the limit of the ROCKE-3D radiation tables.
diverge considerably above an altitude of ~100 km (ref. 75). Since only ~3% of the sunlight incident at the top of the atmosphere reaches the surface, almost all of the solar energy absorbed by the planet is deposited into the atmosphere76. Despite the slow rotation and almost zero eccentricity and obliquity, the atmosphere of Venus consistently produces convective cells, which results in a non-uniform atmospheric circulation75. Furthermore, the turbulence produced in the atmosphere may be the driver for the super-rotation of the middle and upper atmosphere77, which rotates 60 times faster than the solid planet, and may play an important role in the dynamics of many exoplanetary atmospheres78. The super-rotation for terrestrial planets differs from that for giant planets, such as Jupiter and Saturn, due to the interaction of terrestrial atmospheres with the solid planet and the internal heat flux and interior convection of giant planets, which provides an additional driver of super-rotation in the cloud top layers79. The atmospheric super-rotation observed for Venus (and also Titan) and the mechanisms that drive them thus remain a significant challenge for numerical models80.

Climate simulations of tidally locked planets have produced strong evidence that climates can interact significantly with surface topography81,82. Such evidence has been observed directly in the Venusian atmosphere: for example, in the detection and subsequent analysis of stationary gravity waves detected using data from the VEGA Balloon83,84, and the Venus Express mission85. These observations were verified by data from the Akatsuki mission, which indicate the presence of stationary waves in the upper atmosphere of

Venus85, as shown in Fig. 4. The centres of the wave features, visible in the brightness temperature maps (Fig. 4a–c), are located approximately above the Aphrodite Terra highland region, which suggest
that they are the direct result of deep atmosphere movement over, and interaction with, the elevated terrain\textsuperscript{85}. The structure of these waves is not uniform, indicating a dependence on latitudinal and diurnal effects, and thus that their production results from a complex interaction between atmospheric dynamics and solar heating\textsuperscript{86}. The explanation of the atmospheric features as stationary gravity waves was further validated via numerical simulations that also contribute to the atmospheric torque that acts upon the solid planet\textsuperscript{87}. This interplay between incident flux, rotation, atmospheric dynamics, and topography leads to correlated behaviour that is important to include in simulations and may also enable inferences regarding surface conditions and topography.

**Observational diagnostics**

Exoplanet searches to the present date have a limited list of observable parameters, most of which pertain to the orbital properties of the planet\textsuperscript{88}. These observables include orbital period and eccentricity, and planet mass and radius. The next significant step forward is expected to lie in the systematic detection and inventorying of atmospheric compositions via transmission spectroscopy using the James Webb Space Telescope (JWST)\textsuperscript{22,89}. Though the majority of planets studied in this manner will probably be gaseous in nature, strategies have been formulated for addressing the challenge of terrestrial planet atmospheres\textsuperscript{90–93}. Such methodology will be adapted with improved precision to distinguish between the spectral signatures of Earth and Venus in an exoplanet analogue context\textsuperscript{94–96}. For example, Fig. 5 shows the spectra of Venus, Earth and Mars at visible to near-infrared (NIR) wavelengths\textsuperscript{97}. The high optical depth of the Venustian atmosphere results a small fraction of the upper atmosphere being sampled via transmission spectroscopy, neglecting the entire troposphere, which contains 99% of the atmosphere by mass. The CO\textsubscript{2} absorption bands expected for Venus are relatively narrow compared with the broad O\textsubscript{3} and H\textsubscript{2}O absorption features for Earth's atmosphere, due to the truncation of absorption features caused the Venustian cloud decks, and the higher temperature of Earth's atmosphere at high altitudes. Much attention is directed toward the CO\textsubscript{2} absorption bands centred at 2.7 and 4.3 μm due to their potential detectability with the JWST. However, given the subtle difference in absorption features at these wavelengths for Venus and Earth analogues, distinguishing between such planets using transmission spectroscopy may require a broader wavelength criterion, or the identification of Earth-based absorption features such as O\textsubscript{3} (refs. 90,98). As it is expected that many of the transmission spectroscopy targets from transit surveys will be Venus analogue candidates\textsuperscript{45,99,100}, the disconnect between the available observables, fraction of atmosphere probed by transmission spectroscopy and degeneracy of models that infer surface conditions may present a significant barrier to a complete characterization of terrestrial exoplanets in the near future.

In the era of exoplanet direct imaging, the reflectance and emission spectra of terrestrial planets provides an additional means to characterize their atmospheres\textsuperscript{101–106}. Analysis of disk-integrated reflectance spectra for directly imaged exoplanets enables access to short-wavelength absorption and Rayleigh-scattering features, similar to those shown in Fig. 5, that can significantly aid in breaking degeneracy in atmospheric retrieval models. Thermal emission spectra are measured at longer wavelengths and reveal the temperature properties of the cloud layers, and possibly the surface via infrared observing windows. In the context of Venus, such observational diagnostics are incredibly powerful methods to probe the deeper atmosphere through observing windows that penetrate the cloud and haze layers, which are largely opaque at optical wavelengths. NIR observations of the nightside of Venus have successfully probed beneath the sulfuric acid haze layer to measure compositions and mixing ratios present in the middle and deep atmosphere\textsuperscript{105–108}. Remarkably, these NIR observations also reveal surface emissivity and topographical features. As described in Venus atmospheric dynamics, the temperature, pressure and compositional profile of the Venusian atmosphere is critical for a full model evaluation of the complex climate dynamics and how these relate to the spin state of the planet. Thus, the combination of transmission, reflectance and emission spectra will provide key diagnostics for establishing the climate state of exoplanets, whose evolution may similarly be related to the planetary rotation\textsuperscript{109}.

Alternatively, a collaborative approach to exoplanet characterization between direct and indirect detection techniques may aid in resolving potential atmospheric model degeneracies. In addition to planetary mass, radius and spectroscopy of the upper atmosphere, additional parameters of rotation, obliquity, atmospheric dynamics and surface topography are needed to fully constrain surface conditions. In particular, Venus atmospheric dynamics serve as a warning with regards to confusing solid planet with atmospheric rotation, and the interaction between atmosphere and topography. Shown in the left-hand panel of Fig. 6 is a high-resolution image of Venus acquired by the Akatsuki mission. By contrast, the right-hand panel shows the same data convolved to a 5 pixel×5 pixel image, where a noise model has been included to incorporate systematic instrumentation effects. Even this image resolution is optimistic for
exoplanet imaging in the short term, and yet the task of extracting reliable planetary parameters is challenging\textsuperscript{15}. However, the trajectory of future exoplanet mission planning lies in solving such challenges and directly detecting terrestrial exoplanets\textsuperscript{15}, the vast majority of which are invisible to the transit method of detection and characterization. The Nancy Grace Roman Space Telescope, equipped with a coronagraph, will serve as a pathfinder and technology demonstration for achieving exoplanet direct imaging goals\textsuperscript{15}. Mission concepts such as LUVOIR\textsuperscript{15} and the Habitable Exoplanet Observatory (HabEx) Mission Concept Study\textsuperscript{14} will be crucial next steps toward a full terrestrial characterization. The expected limited signal-to-noise ratio of these data must be convolved with the important lessons learned from the Venusian atmosphere to properly interpret the dynamics of the plethora of tidally locked planets that await observation.

Conclusions

With the marked rise in exoplanet discoveries, particularly within the terrestrial regime, the need to fully characterize the limited inventory of terrestrial atmospheres within the Solar System is more important than ever\textsuperscript{2,15,15}. Exoplanetary science is now investing in the task of detecting and interpreting exoplanet atmospheres, which is a substantial observational and modelling undertaking. In the near term, many of the exoplanets studied in this fashion will have been detected via the transit technique. The consequence of this detection source is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The majority of which are invisible to the transit method of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the transit technique of detection. The consequence of this detection technique is a strong bias toward short-period planets, which will generically dominate the short-term mission planning lies in solving such challenges and directly detecting terrestrial exoplanets, the vast majority of which are invisible to the transit method of detection and characterization. The Nancy Grace Roman Space Telescope, equipped with a coronagraph, will serve as a pathfinder and technology demonstration for achieving exoplanet direct imaging goals. Mission concepts such as LUVOIR and the Habitable Exoplanet Observatory (HabEx) Mission Concept Study will be crucial next steps toward a full terrestrial characterization. The expected limited signal-to-noise ratio of these data must be convolved with the important lessons learned from the Venusian atmosphere to properly interpret the dynamics of the plethora of tidally locked planets that await observation.

Data availability

Figure 1 used data from the NASA Exoplanet Archive, available here: https://exoplanetarchive.ipac.caltech.edu/. Figure 3 used output data from ROCKE-3D simulations in netCDF format\textsuperscript{39}. Figure 6 used data from the Akatsuki Science Data Archive, available here: https://darts.isas.jaxa.jp/planet/project/akatsuki/. The data from Figs. 1, 3 and 6 are available here: http://stephankane.net/tidallyevolved

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