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Spinning worlds
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Cover Page

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Summary

A little more than two decades ago, the first planet orbiting a different star than our own Sun was discovered. The existence of such foreign worlds had long been assumed, but little did we know that the Galaxy is, in fact, brimming with planetary systems. They are called exoplanets, which is short for extrasolar planets, to highlight that they are located outside of the Solar System. In the years since that first discovery, thousands of exoplanets have been discovered using several different observational techniques, and new methods have been developed to study their orbits, their composition and their atmospheres.

The study of exoplanets is a quest to understand our place in the universe. How unique is the Solar System? How extraordinary is Earth? Is life on Earth an unfathomable coincidence, or is the Milky Way teeming with life? One of the biggest surprises so far has been the amazing variety in the composition and orbits of the discovered exoplanets. There are planets orbiting their stars in the span of a single day on Earth, and yet others take thousands of Earth-years to complete a single orbit. While some systems have multiple planets or even multiple stars, others consist to the best of our knowledge of a single star and planet. The diversity of exoplanets presents a challenge to the theories of formation designed to match the Solar System, and any modern theories must strive to explain the full observed range of architectures of planetary systems.

This thesis deals with two different types of gas-giant exoplanets, representing the opposite extremes in terms of the orbits: Hot Jupiters and young, wide-orbit gas giants. A hot Jupiter is a gas giant with a mass similar to that of Jupiter, but it has an orbital period of fewer than five days. The proximity to the star leads to soaring temperatures, and many of these planets have been found to have much larger radii than Jupiter in spite of the similar masses. The wide-orbit gas giants, on the other hand, typically have distances to their star that are tens or hundreds of times further than the distance between Sun and Earth. These exoplanets have been detected with direct imaging, meaning the star and the planet appear as two separate objects in astronomical images. This is possible because of the wide orbit,

and yet, only if the gas giant is extremely hot. The distance from the star is too large to heat the planet atmosphere significantly, but if the system is young - up to a couple of hundred million years - the planet will still be hot from the formation. Although direct imaging is currently limited to young exoplanets, this also provides a unique opportunity to study planets at the earliest stages of their lives.

Observing exoplanet atmospheres

Depending on how an exoplanet is discovered, some of the basic physical properties, such as the mass and radius, can be estimated directly from the detection. However, detection is only the first step in understanding the physical properties of an exoplanet. The characterisation of its atmosphere is the next. It can reveal the chemical composition of the atmosphere, and as is shown in this thesis, the temperature structure and the rotation of the planet. Ultimately, we want to find evidence for biological activity through the detection of biomarker gases in the atmosphere – such as molecular oxygen in the atmosphere of Earth.

The planet detection methods are mostly indirect, meaning that the light from the star and the planet are mingled, and the presence of the planet is inferred from the light of the star. For atmospheric characterisation, it is necessary to separate the planet light from that of the star. This can be done in several ways. The most successful methods so far are applied to transiting exoplanets. These are exoplanets where the orbit by chance is oriented such that the planet passes in front of the star as seen from Earth. The methods are based on how the contribution from the planet to the observed light (star+planet) changes periodically. The planet disappears behind the star, emerges again, gradually changing the amounts of day-side and night-side as viewed from Earth, and then when the planet transits in front of the star, a part of the stellar light is filtered through the planetary atmosphere, leaving a sort of fingerprint in the observed light. In the case of the directly imaged, wide-orbit exoplanets, the light from the planet can be separated directly to different pixels than those of the star, although starlight will inevitably scatter to the position of the planet as well. In this thesis, I combine the methods mentioned above with high-resolution infra-red spectroscopy. This provides an additional filtering mechanism because the spectrum of the star is different from that of the planet.

The vertical temperature structure of a hot Jupiter

An important aspect of any exoplanet atmosphere is how the temperature changes with altitude. Generally, the radiation from the star penetrates deeply into the atmosphere of the planet, heating it from below. This causes the temperature to drop with increasing altitude. However, strong optical or UV absorbers in the upper layers of the atmosphere can result in a layer or region in the atmosphere where the temperature instead *increases* with altitude. The temperature is *inverted*. Such temperature inversions are common among Solar System planets. Jupiter, along with the other giant planets, has thermal inversions caused by CH_4-induced hazes, while O_3 causes the inversion in Earth's stratosphere.

Thermal inversions may be commonly present in hot Jupiter atmospheres as well. There have been claims of inversion layers in several hot Jupiter atmospheres, mostly based on observations with the Spitzer Space Telescope. While these claims are intriguing, they have also proven controversial and prone to degeneracies. In Chapter 2, I present the results from high-dispersion near-infrared spectroscopic observations of the famous hot Jupiter, HD 209458 b. This exoplanet was long considered the gold standard for a hot Jupiter with a thermal inversion; however, we found evidence *against* a strong thermal inversion. Our observations are best explained by a temperature which hardly changes with altitude.

A first survey of the rotation of exoplanets

The Earth rotates around its own axis and this determines the length of night and day. The rotation influences the climate, the atmospheric dynamics, and the magnetic field of a planet. Therefore, the ability to measure the rotation period for exoplanets is of great importance. Besides, it may shed light on the formation process and evolution.

Two formation processes are typically considered for giant planets: i) core accretion and ii) disk fragmentation. Jupiter and Saturn are commonly accepted to have formed through core accretion. In this class of formation models, gas accretes onto solid planetary embryos of several to ten Earth masses that may have formed at distances comparable to that of Jupiter. The discovery of extrasolar giant planets with extremely wide orbits led to the reinvigoration of the disk fragmentation hypothesis because the core accretion scenario struggles to explain the existence of planets so far from the star. This theory states that giant (exo)planets may form as a disk gravitational instability that collapses on itself in the outer protoplanetary disk. Planetary rotation is predominantly a result of accretion of angular momentum during the formation, and if core accretion and gravitational instability result in differences in spin angular momentum, it is possible this will show up in studies of the rotation of substellar companions as a function of mass or orbital distance from the star.

Our team has performed a small survey aimed to determine the rotation velocities of young, wide-orbit exoplanets. The observations combine high-resolution spectroscopy with high-contrast imaging, and this ground-breaking technique has resulted in the first measurements of the rotation of exoplanets. In practice, what we measure is the *projected* rotational velocity. This means the component of the rotation velocity along the line-of-sight, and the velocities are as such minimum values. In Chapters 3, 4, and 5, I present the results from three individual objects, and in Chapter 5 I also study the rotation of the sample as a whole. I investigate the rotation as a function of mass, orbital distance and age. Although the observed sample is small, we do see a correlation of rotation velocity with age, which we interpret as due to the youngest objects still accreting material and angular momentum and their spin up through subsequent cooling and contraction.