Spinning worlds
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1 Introduction

"They say the sky is the limit, but to me, it is only the beginning. I look to the stars, and I count them, imagining every one of them as the centre of a solar system, even more wondrous than our own. We now know they are out there. Planets. Millions of them – just waiting to be discovered. What are they like, these distant spinning worlds? How did they come to be? And finally – before I close my eyes and go to sleep, one question lingers. Like the echo of a whisper : Is anyone out there..."

The study of exoplanets is a quest to understand our place in the universe. How unique is the solar system? How extraordinary is the Earth? Is life on Earth an unfathomable coincidence, or is the galaxy teeming with life? Only 25 years ago the first extrasolar planets were discovered, two of them, orbiting the millisecond pulsar PSR1257+12 (Wolszczan and Frail, 1992), and this was followed three years later by the discovery of the first exoplanet orbiting a solar-type star (51 Pegasi, Mayor and Queloz, 1995). In the subsequent years, multiple techniques were developed to find and study these new worlds. Each detection method has its own advantages, limitations and biases, and they have complimented each other to form the picture of exoplanets that we have today: The galaxy is brimming with planetary systems, and the exoplanets are more diverse, than we could ever have imagined.

The diversity of planets 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. In fact, understanding the formation and evolution of planetary systems and exploring their full diversity and complexity is one of the central themes of contemporary astrophysics today. Ultimately, we wish to answer fundamental existential questions about the possible occurrence of extraterrestrial life. The search for life outside the solar system may commence less than a decade from now by searching for atmospheric gases in chemical disequilibrium such as molecular oxygen in the atmosphere of the Earth.

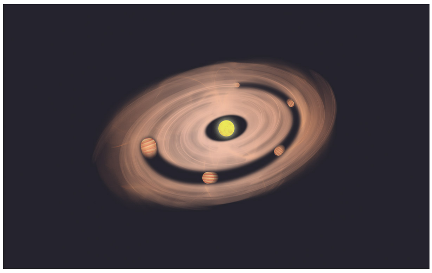
1.1 Star and planet formation

Stars form through the gravitational collapse of prestellar cloud cores, which are gravitationally bound, dense regions within a larger molecular cloud. The continued infall of mass from the outer layers cause the core to become opaque, and the temperature to increase (Larson, 1969; Boss and Yorke, 1995). When the temperature in the core reaches 2000 K, molecular hydrogen is dissociated and hydrogen and helium atoms are ionized, absorbing energy, and allowing the core to contract and accrete further to form a protostar surrounded by an envelope. Due to rotation, a centrifugally supported disk will form (Terebey et al., 1984), and accretion onto the newly formed protostar is mostly continued through this circumstellar disk. At the moment that the accretion stops, the star is considered a pre-main-sequence (PMS) star which is powered by the energy from the gravitational collapse. Hydrogen fusion will occur when the core temperature in the PMS star is high enough, thus entering the star into its main sequence life time.

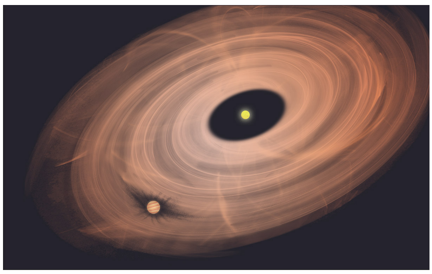
It is expected that during the phase that the protostar harbours a circumstellar disk (also called a protoplanetary disk) not all material accretes onto the star, but instead forms planets. This is a complex process which is yet far from fully understood. Since this thesis deals with giant gaseous planets, I will focus here on outlining current views on particularly their formation.

The currently favoured theory for giant planet formation is core accretion (Fig. 1.1A, Pollack et al., 1996; Laughlin et al., 2004; Hubickyj et al., 2005). This is an accumulative process taking place within the protoplanetary disk, from dust and grains which coagulate into larger particles, settling towards the disk midplane eventually forming kilometer sized planetesimals which grow to planetary embryos through collisions, rapidly growing to a protoplanet. Once the planetary core grows large enough, it attracts a gas envelope, slowly at first, however as the total mass exceeds the point where the gravitational force is balanced by the pressure gradient, runaway accretion will take place. Eventually the accretion rate will decrease as the surrounding gas is depleted. Core accretion is expected to be most effective beyond the ice line, between 5 and 10 au. The existence of hot Jupiters with periods on the order of days, are explained with either type II migration within the disk, or as dynamical scattering through gravitational interactions with additional bodies (Chambers, 2007). However, it has also been suggested that hot Jupiters may form by core accretion in situ, initiated by the presence of super Earths (Batygin et al., 2016). Planets can also be scattered in the outward direction, and this is a possible explanation for the existence of the extremely wide-orbit companions which have been discovered with direct imaging techniques.

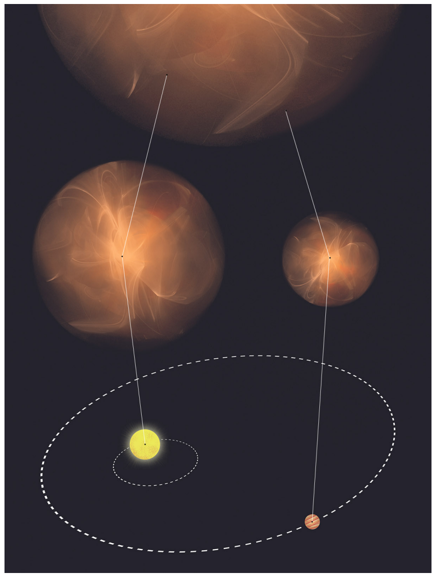
The major contesting theory for giant planet formation is the disk gravitational



(A) Core Accretion



(B) Disk Instability



(C) Prestellar Core Fragmentation

Figure 1.1: The two most common formation theories for giant planets are (A) core accretion, and (B) disk instability. In the core accretion model, the planet agglomerates from dust, typically at a distance of 5-10 au, and once the planetary core grows large enough it attracts a gas envelope. The planet may subsequently migrate inwards through type II migration or be scattered in either direction. In the disk instability model, a clump of gas collapses in the outer part (> 40 au) of a massive circumstellar disk. A third option, (C) prestellar core fragmentation, is considered for wide-orbit giant planets and brown dwarf companions. This model considers gravitational instabilities that takes place at a much earlier stage of the star's evolution, and it is equivalent to how binary star systems are formed. *Image credit: Rafa Monterde Alonso.*

instability model (Fig. 1.1B, Boss, 1997, 2000), which states that gas giants might form from a gravitational collapse within the protoplanetary disk. Gravitational instabilities lead to fragmentation of the gas into self-gravitating clumps. The majority of the mass is accumulated on a much shorter timescale compared to core accretion, and only later will a core form through sedimentation. The exact conditions for gravitational instabilities to occur are debated, but disks with large masses, low temperatures and high densities are favoured. Furthermore, disk instabilities are only expected to take place in the outer parts of a disk, at several tens to hundreds of au, because the radiative cooling rates there are higher (Cai et al., 2006; Rafikov, 2007).

In the case of wide-orbit giant planets and brown dwarf companions there is a third formation pathway which may play a significant role (Fig. 1.1C). During the earliest stages of the prestellar cloud collapse, the prestellar core can fragment due to global non-linear gravitational instabilities(Chabrier et al., 2014). This is how binary stars are expected to form, and it is possible that that the same process can produce an object pair with an extreme mass ratio (Jumper and Fisher, 2013), forming a system with a central star and a wide-orbit giant planet. This theory is supported by the existence of substellar companions with large projected separations in the range 500 au to 3500 au and masses down to 5 M_J (Aller et al., 2013). The scale of these systems is much larger than that of protoplanetary disks, but is a good match to prestellar core envelopes.

The three formation pathways described here have one thing in common. They all struggle to explain the whole observed spectrum of giant planets. Therefore it is a distinct possibility that all of them can take place, depending on the conditions of the forming star system. While core accretion is expected to operate most efficiently relatively close to the star, disk instabilities is only expected to take place in the outer regions of the protoplanetary disk, and prestellar core fragmentation may explain some of the widest orbiting companions, although it may also be possible to form tight binaries during the prestellar core collapse (Bonnell and Bate, 1994). This opens up the idea that the orbital distance of an exoplanet can be used as an indicator for how the planet was formed. However, this will need to be treated in a statistical sense, since migration and dynamical scattering complicates the situation, with planets potentially having formed in a very different orbit than the one where they are presently observed (Vorobyov, 2013).

In this thesis we focus on a new observable, the rotational velocity, which may shed some light on the formation of giant planets, as well as brown dwarf companions. The spin angular momentum of an exoplanet is accreted together with the mass, during the formation. Therefore it is conceiveable that the initial spin angular momentum content is strongly related to how the planet formed, and that for example core accretion and disk instability with their different time scales and favoured locations within the disk, will result in observable differences in the spin rate. It is important to realise that the spin will evolve, and that the evolution is mass dependent. It will be necessary to fully understand this evolution if we are to use measurements of the rotational velocity, or alternatively the rotation period, to probe the formation of exoplanets.

1.2 Finding exoplanets

Finding extrasolar planets is extremely challenging. For a distant observer, the reflection of the Earth only adds up to less than 1 part-per-billion of the light from the Sun. Fortunately, there are several methods to indirectly infer the presence of extrasolar planets. The radial velocity method, astrometry, and pulsar timing all make use of the orbital motion of the host star around the center-of-mass of the extrasolar planetary system – without directly seeing the planet. In particular the radial velocity method has been extremely successful with more than a thousand detections to date, providing the main orbital parameters and a lower limit to the planetary mass. Also the transit method has been a flourishing success, not least due to the Kepler mission, which has discovered more than 2300 confirmed exoplanets[1]. The transit method relies on near-perfect alignment of the orbit with the line of sight, so that the planet transits in front of the star, causing periodic dips in the light curve. This provides a measure of the planetary radius, and combined with the radial velocity method, this in turn gives an estimate of the mean density of the planet, constraining its bulk composition. While the radial velocity and transit methods are strongly biased towards planets on close-in orbits, astrometry, which measures the on-sky displacement of the host star, will excell at detecting long-period planets, and it will be more sensitive to planets with an orbital plane which is viewed face-on. Although no exoplanets have been discovered as of yet by astrometry, the ESA GAIA mission is expected to find thousands of exoplanets unlocking a whole new area of orbital parameter space (Perryman et al., 2014). The existence of an extrasolar planet can also be inferred from microlensing through which distant background stars are lensed by foreground planetary systems. Although this has resulted in the detection of a few dozen planets, their properties can only be inferred in a statistical sense.

Direct detection of exoplanets by high contrast imaging is still very challenging, but great progress is being made. So far it is restricted to young massive planets which are still hot from their formation, of which about two-dozen are known. These observations provide a direct measure of the flux from the planet, thereby

[1]http://exoplanetarchive.ipac.caltech.edu/

immediately probing the planetary atmosphere. Since the achieved contrasts near the host star are still limited, most planets discovered are located at projected separations of tens to hundreds of au. The theoretical observational limits are a stong function of telescope size, and the future holds great promise with the European Extremely Large Telescope (E-ELT). The E-ELT and other extremely large telescopes are expected to open up the parameter space to include signifantly cooler and older planets - even mature planetary systems around the nearest stars.

The combination of all these techniques, each with their own specific biases, have provided a first view of the planet population (Fig. 1.2). It has revealed that planets are very common. More than 10% of the solar type stars have gas giant planets of Jupiter mass, $\sim$30% have super-Earth to Neptune-size planets (Mayor et al., 2011), with the occurrence rate increasing for smaller radii (Howard et al., 2012). An extrapolation to Earth-mass planets is speculative at best, but it is likely that most stars harbour Earth-mass planets. While the solar system planets already exhibit an enormous diversity, this is extended even further in the exoplanet population. New classes of planets, such as hot Jupiters, super-Earths and massive gas giants on wide orbits, are all common but not found in the solar system. Discoveries are being pushed to smaller and more temperate planets, both using the transit and radial velocity method. The most exciting recent example has been the discovery of a terrestrial planet in the habitable zone of our nearest neighbour Proxima Centauri (Anglada-Escudé et al., 2016).

1.3 Atmospheric characterisation

Detection is only the first step in understanding the physical properties of an exoplanet. The characterisation of its atmosphere is an important next step. It can reveal the chemical composition of the atmosphere, its reflective properties, the presence of condensates, its temperature structure, and possible rotation and global circulation. Those may be linked to the formation and evolutionary history of the planet, and are needed to understand its global climate. Also the information on the atmosphere may shed light on the bulk composition of the planet, which in the case of only mass-radius information may result in persistent degeneracies. Ultimately, we want to find evidence for biological activity through the detection and identification of biomarker gases that are out of chemical equilibrium – such as molecular oxygen in the atmosphere of Earth. To reach this exciting goal a deep understanding of the possibly wide range of planet families, their atmospheric processes and evolutionary histories is required.

The planet detection methods are mostly indirect, meaning that no flux from the planet is identified. For atmospheric characterisation it is necessary to separate

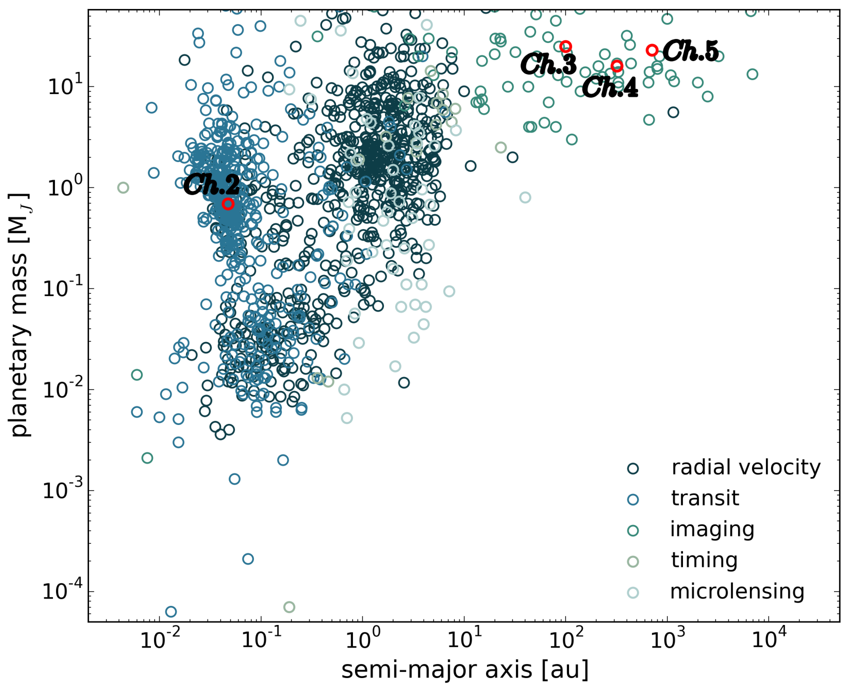


Figure 1.2: The exoplanet.eu catalog as of December 2016. The planets (or brown dwarf companions) which are featured in this thesis are marked with their respective chapters. One is the hot Jupiter HD 209458 b (Chapter 2), and the three others are direcly imaged substellar companions, GQ Lupi b (Chapter 3), GSC 6214-210 b (Chapter 4), and HIP 789530 b (Chapter 5).

the planet light from that of the star. This can be done in several ways. Most successful so far have been atmospheric observations of transiting planets for which time differential measurements are made, including transits, eclipses and phase curves. In addition, planet light can be angularly separated like in the case of direct imaging. As used in this thesis, these methods can be combined with high-dispersion spectroscopy to further separate the planet light from that of the star and, since these are ground-based obervations, the telluric contamination.

1.3.1 Transits, eclipses, and phase curves

Transiting planets offer unique opportunities for atmospheric characterisation. When the planet passes in front of the star, as seen from Earth, starlight filters through the planetary atmosphere. When observed at different wavelengths, this manifests itself as a wavenlength dependent radius, because more or less star light is absorbed

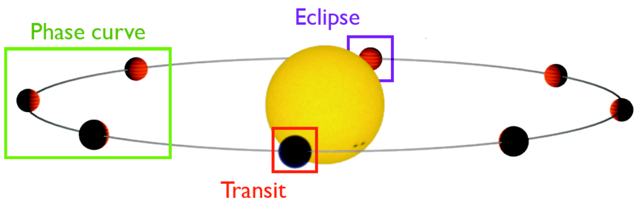


Figure 1.3: Transiting exoplanets provide three distinct methods for characterising the atmosphere of the planet. *Image credit: Ernst de Mooij*

by the planet atmosphere. This is called transmission spectroscopy. These measurements have been very successful from space using the Hubble Space Telescope and Spitzer Space Telescope, resulting in the detection of atomic and molecular gases in the atmosphere and exospheres of hot Jupiters (Charbonneau et al., 2002; Vidal-Madjar et al., 2004), and high-altitude hazes through Rayleigh scattering (Pont et al., 2013). There is also compelling evidence for the existence of high-altitude clouds in some Super-Earths and Neptune-size exoplanets (Kreidberg et al., 2014; Knutson et al., 2014b,a).

Half an orbit later, the planet is eclipsed by its star, offering a moment in time when the observed flux only belongs to the star. This can be subtracted from the observations immediately before or after the eclipse when the day-side of the planet is fully visible, thus revealing the portion of the flux, which belongs to the planet (Deming et al. 2004; Charbonneau et al. 2004). A rough spectrum can be constructed from the broadband measurements of the secondary eclipse depth as function of wavelength, revealing its thermal spectrum and/or reflected spectrum. In addition, molecular features can constrain the temperature structure of the planet.

By monitoring the flux from the planet+star system as function of orbital phase, the varying contribution from the planet's day and night side can be assessed (Knutson et al. 2007), revealing a one-dimensional temperature map of the planet. This can constrain the global circulation patterns of the planet and its overall climate. In the case of optical phase curve observations the planet albedo is being probed.

1.3.2 High-contrast imaging

High-contrast imaging provides a direct way of probing the atmosphere of a planet. The best results are being reached with ground-based telescopes using adaptive optics systems aimed to cancel out seeing effects, and coronography to optimally darken regions directly around the star. Also, smart analysis algorithms are being used to further remove systematics originating from the telescope.

High-contrast imaging immediately allows the planet thermal spectrum to be constructed by combining measurements at different wavelengths (Lagrange et al., 2010). The planet must be located at large enough orbital distance they it can be angularly separated from the host star, typically tens or hundreds of au. This means the irradiation from the host star is negligible, and mature planets at such orbital distances are too faint, and out of reach of the current telescope systems. On the other hand, the very young planets can be observed (Marois et al., 2008; Lagrange et al., 2010), because they are still hot from their formation, resulting in a much more favourable planet-to-star contrast. This provides a unique opportunity to study exoplanets in their infancy.

1.4 High-dispersion spectroscopy

Ground-based high-dispsersion spectroscopy in the near-infrared has proven to be an effective method to probe both transiting hot Jupiters as well as young directly imaged gas giants. With a sufficiently high spectral resolution the molecular features are resolved into individual lines, allowing a reliable identification of the molecules through line matching with template spectra (Brown et al., 2002; Deming et al., 2005; Barnes et al., 2007). Our team has successfully employed two different strategies for isolating a planetary signal from its host star, using the Cryogenic Infra-Red Echelle Spectrograph (CRIRES; Kaeufl et al., 2004) at the Very Large Telescope (VLT). The first is time-differential observations which has been applied to hot Jupiters (Snellen et al., 2010), and the second is a combination with high contrast imaging, targeting the spatially separated gas giants, discovered with direct imaging(Snellen et al., 2014).

1.4.1 High-dispersion spectroscopy for time-differential observations

CRIRES has a spectral resolving power $\lambda/\Delta\lambda \simeq 100\,000$, which is sufficient that molecular bands, such as the ro-vibrational (2,0) R-branch of carbon monoxide (CO), are resolved into tens or hundreds of individual lines. This means the observations become sensitive to Doppler effects related to the orbital velocity of the planet. In the case of hot Jupiters the orbital velocity can be up to 150 $\mathrm{km\,s^{-1}}$, so within a few hours of observations the radial component can change up to tens of $\mathrm{km\,s^{-1}}$ corresponding to tens of pixels in the observed spectrum. This allows the shifting planet spectrum to be effectively filtered out from the quasi-stationary stellar and telluric spectral features. This method can be applied to any system in which the planet velocity is expected to vary, including transit and dayside measurement, for which the latter can also be applied to non-transiting systems (Brogi et al., 2012).

CRIRES hot Jupiter survey

Snellen et al. (2010) was the first to successfully implement the high-dispersion time-differential strategy to detect CO at 2.3 μm in the transmission spectrum of the hot Jupiter HD 209458 b. This was followed by a large CRIRES survey targeting five of the brightest hot Jupiters, two of them transiting and three of them non-transiting. Table 1 summarises the published results from high-dispersion infrared spectroscopy of hot Jupiters both from the survey by our team and from other teams. The observations are a mix of transmission spectroscopy and dayside spectroscopy, and they have provided robust detections of CO and/or H_2O in the atmospheres of the targeted hot Jupiters, along with constraints on their abundances. For the three non-transiting planets, 51 Pegasi b, HD 179949 b and τ Boötis b, the absolute masses and inclinations have been measured (Brogi et al., 2012, 2013, 2014; Rodler et al., 2012; Lockwood et al., 2014), a feat which has so far only been achieved with this method. While transmission spectroscopy will always result in molecular *absorption*, dayside spectroscopy is sensitive to the temperature-pressure (T/p) profile, because the line-of-sight is near-aligned with the vertical direction in the planetary atmosphere. The T/p profile affects the average shape of the absorption lines in the dayside spectrum, with the most extreme example being a temperature inversion layer in the atmosphere which would result in emission lines rather than absorption lines in the dayside spectrum. However at the current time, only absorption has been detected (See Chapter 2). Also planet rotation can affect the shape of the spectral lines, and atmospheric circulation can cause an additional Doppler shift. Brogi et al. (2016) constrained the average line shape of CO and H_2O absorption lines in the transmission spectrum of HD 189733 b, and found their measurements to be consistent with synchronous rotation, which is the expectation for a hot Jupiter, and a small day- to nightside wind peed of $-1.7\,\mathrm{km\,s^{-1}}$.

1.4.2 High-dispersion spectroscopy + high-contrast imaging

High-dispersion spectroscopy can also be combined with high contrast imaging (HDS+HCI). While the planet-star contrast obtained with HCI may not be sufficient to detect the planet, the remaining starlight at the planet position may have a significantly different spectrum than that of the planet. The stellar spectrum is well sampled and can be filtered out, leaving only the planet signal at the planet

Table 1.1: Summary of hot Jupiters observed with high-dispersion spectroscopy

Planet	Method	Wavelength	Molecule	Reference	Note
Transiting planets					
HD 209458 b	Transmission	2.3 μm	CO	Snellen et al. (2010)	Pilot study
	Dayside	2.3 μm	(CO)	Schwarz et al. (2015)	Chapter 2
HD 189733 b	Transmission	2.3 μm	CO+H_2O	Brogi et al. (2016)	
	Dayside	2.3 μm	CO	de Kok et al. (2013)	
	Dayside	3.2 μm	H_2O	Birkby et al. (2013)	
Non-transiting planets					
51 Pegasi b	Dayside	2.3 μm	CO+H_2O	Brogi et al. (2013)	
HD 179949 b	Dayside	2.3 μm	CO+H_2O	Brogi et al. (2014)	
τ Boötis b	Dayside	2.3 μm	CO	Brogi et al. (2012)	
	Dayside	2.3 μm	CO	Rodler et al. (2012)	diff. team, CRIRES
	Dayside	3.2 μm	H_2O	Lockwood et al. (2014)	diff. team, NIRSPEC

Unless stated otherwise in the notes, the observations listed here are part of a CRIRES survey conducted by our team. The dayside detection of CO in the atmosphere of HD 209458 b is only tentative, and is therefore in a paranthesis.

position, and the signal of the individual spectral lines can be combined again by using cross-correlation techniques (Sparks and Ford, 2002; Riaud and Schneider, 2007; Snellen et al., 2015). In this way the spin-rotation of the directly imaged planet β Pictoris b was determined for the first time (Snellen et al., 2014).

1.5 This thesis

In this thesis I characterise giant exoplanets using ground-based high-dispersion spectroscopy, both targeting young directly imaged gas giants and a transiting hot Jupiter. This involved the two observational techniques as described above, time differential spectroscopy and a combination of spectroscopy and high-contrast imaging. Chapter 2 describes CRIRES observations of the famous hot Jupiter HD 209458 b, constraining its atmospheric vertical temperature structure. Chapters 3, 4, and 5 present the first mini-survey of planetary spin measurements.

1.5.1 Chapter 2 - Evidence against a thermal inversion in a hot Jupiter

The vertical temperature structure is one of the prime objectives in the atmospheric characterisation of an exoplanet. There have been claims of temperature inversion layers in a selection of strongly irradiated hot Jupiters, but the claims have been based on broadband secondary-eclipse measurements which suffer from degeneracies between the molecular abundances and the temperature structure. On the other hand, high dispersion spectroscopy has the potential to unambigously detect the presence of a temperature inversion layer. If molecular emission lines are identified in the spectrum, this can only be explained by the presence of a thermal inversion.

In Chapter 2, we present the results from high-dispersion near infrared spectroscopic observations of the dayside of HD 209458 b. This was one of the objects in the hot Jupiter CRIRES survey described in Section 1.4.1. 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. Although CO is known from transmission spectroscopy to be present in the atmosphere of HD 209458 b, in the dayside spectrum, we saw only a hint of an *absorption* signal from CO. This is best explained by a near-isothermal pressure profile.

1.5.2 Chapters 3, 4 & 5 - first survey of planetary spin

The rotational velocities of exoplanets and brown dwarf companions are fundamental observables which affect their climate, atmospheric dynamics, and magnetic fields, and may hold important clues to the formation process and the orbital history of these objects. We have measured the projected rotational velocity of three young substellar companions, GQ Lupi b (Chapter 3), GSC 6214-210 b (Chapter 4), and HIP 78530 b (Chapter 5), showing $v \sin(i)$ of $5.3^{+0.9}_{-1.0}$ km s^{-1}, 21.5±3.5 km s^{-1}, and $12.0^{+2.0}_{-1.5}$ km s^{-1}, respectively. Combining this small sample with the previously observed objects Beta Pictoris b (Snellen et al., 2014) and 2M1207 b (Zhou et al., 2016), I made a first attempt to conduct comparative planetology with the spin as the focus. A correlation is seen of spin velocity with age, which we interpret as due to the youngest objects still accreting angular momentum and their spin-up through subsequent cooling and contraction.

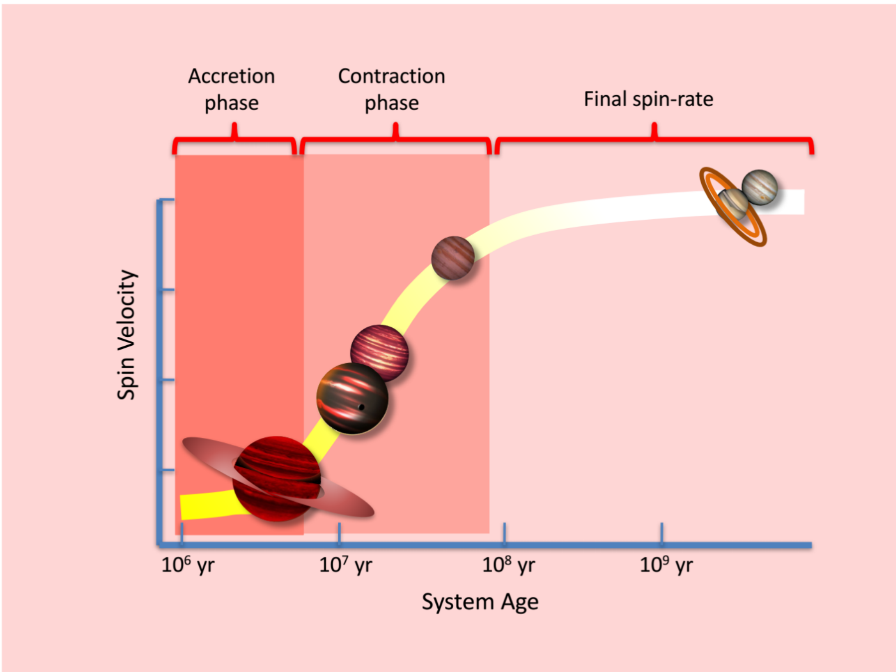


Figure 1.4: Graphical illustration of the proposed spin and angular momentum evolution of gas giant planets (Chapters 3, 4, and 5).

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