Stars and planets at high spatial and spectral resolution

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Chapter 1

Introduction

Light has told us nearly everything about the cosmos we know today. With our ability to measure its characteristics more and more accurately, our understanding of the universe has increased dramatically.

Since the invention of the telescope 400 years ago, enormous progress has been made in the angular and spectral resolution of telescopes, and in increasing the range of wavelengths over which electromagnetic waves can be measured. This development has made a profound impact on our understanding of the formation and evolution of stars and planetary systems. Space-based observatories, such as IRAS, ISO, and Spitzer, have opened up the infrared spectral window, which have allowed the investigation of interstellar clouds as birth-places of stars, and the study of circumstellar disks from which it is thought planets may be formed. The advent of optical/infrared interferometry allows us now to probe the inner parts of these protoplanetary disks, giving insights into their structure, dynamics, and evolution. In parallel to these developments, the recent improvements in the accuracy and stability of optical spectrographs have lead to the dawn of population studies of extrasolar planet systems. It is thought that this progress in instrumental techniques continues to flourish, leading possibly to the direct imaging of Earth-like planets, and planets not at all like our own, in the not too distant future.

The work presented in this thesis involves the development of new instrumental techniques and analysing tools, combining high spectral resolution with high spatial information, with the aim to increase our understanding of the formation and evolution of stars and planets. First, in Chapter 2 a novel instrumental concept is presented that aims to achieve high spatial and spectral resolution by combining existing Echelle spectrographs with existing optical interferometers. Subsequently, several studies combining high spatial and spectral resolution are presented. In the third chapter of this thesis we investigate the immediate environment of the massive young stellar object MWC 349A, using the MIDI instrument on the VLT interferometer. In Chapter 4, new methods are presented to analyse the Rossiter-McLaughlin effect during stellar eclipses. By using this effect it is possible to obtain high resolution spectra from different parts of stellar surfaces, and de facto to obtain spatial information on stellar surface scales, something difficult to achieve by other means. Using these new tools we show that the spin axes in both stars of the V1143 Cyg system are aligned with the orbital spin axis. For the stars in the DI Herculis system, for which we present our results in Chapter 5, the situation turned out to be very different. In this system the axes of both stars are strongly tilted with respect to the orbital angular momentum. This solves a 20 year old riddle about the DI Herculis system, involving its apparently slow apsidal motion, but it presents new challenges for binary formation theories. In the final chapter of this thesis I present sodium measurements for the atmosphere of the extrasolar planet HD 209458b using ground-based transmission spectroscopy.

1.1 The formation of stars and planets in a nutshell

In recent years the research field of single, low-mass star formation has seen an enormous development, both due to new ground-based and space-based instruments and observational techniques, and due to the development of astrophysical theories that support these observations. Star formation occurs in cold dense clouds of gas and dust. While the cloud is supported by magnetic fields and turbulence, the densest regions can collapse under the influence of gravity. At the centre of these dense cores, a star begins to form. During this process it is thought that a circumstellar disk is formed by in-falling material due to its non-zero angular momentum. Accretion from the disk onto the star, is believed to drive bi-polar outflows that help to transport the excess angular momentum away. When the reservoir of cloud material that feeds the disk is exhausted, the accretion rate from the disk onto the star drops. While the star contracts, its temperature increases and the developing stellar winds clear away the remaining material from the cloud. In the disk, planetesimals and finally planets are thought to be able to form. The star, which thus far has generated most of its energy from contraction, is now mainly powered by hydrogen fusion and does not contract anymore. It has reached the main sequence. The surrounding disk is dissipated and the leftover material comprises a debris-disk, possibly with planets.

In the field of star formation the theory of single low-mass star formation, as described above, is most advanced. However, in the fields of the formation of high-mass stars, and the formation of multiple systems, many open questions remain.

1.1.1 Formation of high-mass stars

The processes which lead to the formation of massive stars are not well understood yet (see Zinnecker & Yorke 2007, for a review). The reasons for this are the shorter time scale over which the formation of massive stars occurs, the smaller numbers of massive stars, and the greater distances between us and the nearest regions where massive stars are forming. As an additional consequence of the short times scales over which the formation of massive stars occurs a much greater portion of their formation history is hidden from our view compared to the case for low-mass star formation. Finally, massive stars often form in the densest clusters, making the interpretation of the observations much more difficult.

Nevertheless, the following sequence of events towards the formation of massive stars can be drawn (Zinnecker & Yorke 2007). In a giant molecular cloud, cold dense cores or filaments, possibly formed by supersonic turbulence, generate gravitationally bound pockets of compressed gas. These 10-15K cold cores subsequently collapse under the influence of gravity into optically thick, pressure-supported stellar embryos. This phase is thought to be followed by accretion onto the proto-stellar objects while they evolve towards the main sequence. While for low-mass stars it is believed that the accretion stops before the onset of hydrogen burning, for massive stars it is believed that hydrogen burning already starts while accretion is still ongoing. The young high-mass stars emit a high degree of UV radiation and generate HII regions around them. Furthermore, these high-mass stars generate strong winds during accretion, which will eventually clear their surroundings and disrupt the birth cloud of the star.

Despite having this general picture of massive star formation, many questions are still unanswered. For example, do massive stars always form in dense clusters or can they also form in isolation? What role does binarity play in the formation of massive stars? Can massive stars form through mergers? To what extent have circumstellar disks time to form in the surrounding of these high-mass stars? How long will they survive in the intense radiation field of the massive star, and can planets form in these disks? How does the formation of a massive star shape its environment and influence neighbouring proto-stars? In particular, in what way do they influence the formation of low-mass stars and their planets?

In Chapter 3 we contribute to the efforts of answering these questions by studying the structure of the disk around one isolated young stellar object, which has already dispersed its parent cloud, using the VLT interferometer.

1.1.2 Stellar binaries

Many problems in the field of the star formation, for either low- or high-mass stars, are connected to angular momentum. How do stars slow down their rotation after forming with a rapid spin rate? Do stars in binary systems acquire a common angular momentum and orientation from their parent molecular cloud? How do tidal interactions between stars, and between planets and stars, result in a redistribution of angular momentum among the rotating bodies and their orbits? Most stars (and by extension their planets) are born in double or multiple star systems (e.g. Ghez et al. 1993). Therefore, the problem of binary stars is central to a complete understanding of star formation. It is suspected that even the Sun was once a member of a multiple system, based partly on evidence directly related to observations discussed in this thesis: the observed 7° tilt between the planetary orbits and the solar spin axis (Heller 1993). According to theories of binary star formation, the overall angular momentum distribution is a key determinant (Goodwin et al. 2007), but there are other important aspects of the parent interstellar cloud, such as its geometry, its gravitational and thermal energy, and its magnetic fields. It is important to know the relative influence of these factors on the formation processes (e.g. Bonnell et al. 1992; Larson 2003; Machida et al. 2003). One way to determine the relative importance of angular momentum is by measuring the relative orientation of the stellar spin-axes: for what maximum orbital period are the stars observed to be well-aligned? Until quite recently there had been little hope of answering this question, although there is circumstantial evidence for misalignment in a few very long-period systems (hundreds of years) (e.g Jensen et al. 2004; Skemer et al. 2008). On the other hand, for extremely close binaries, in which the stars are nearly in contact, one can safely assume that tidal forces have co-aligned the stars even if they did not form in that way. Observations between these two extremes have heretofore been unavailable, but they are critical, as they will define the scale length over which the primordial angular momentum was influential.

How can the orientation of stellar rotation axes be measured when even the world's biggest telescopes cannot resolve stellar surfaces to the necessary degree? Optical interferometers have a high enough spatial resolution to (partly) resolve the stellar surfaces. If they would have a high enough spectral resolution to resolve stellar absorption lines, measurements of the colour-differential phase would probe the relative difference in position on-sky between the centroid of the blue-shifted light and the centroid of the rotationally red-shifted light. Measurements at different projected baselines would in this way reveal the orientation of the stellar spin axes

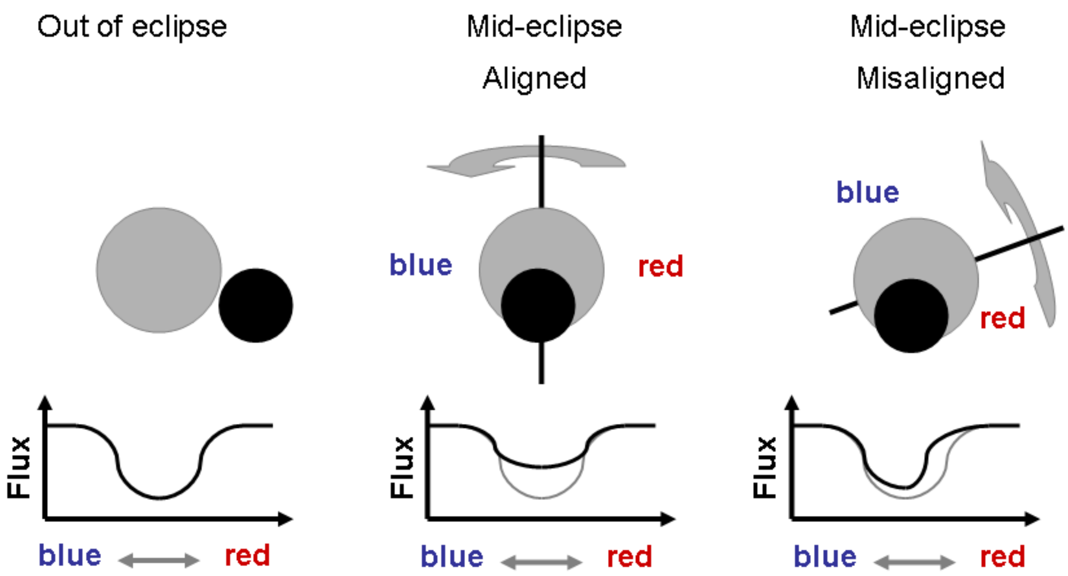

Figure 1.1 — Schematic picture of the Rossiter-McLaughlin effect. Due to stellar rotation, an observed absorption line is broadened (left). A partial eclipse by a foreground object deforms the absorption line differently if the stellar spin axis is aligned (middle panel) or misaligned (right panel).

(Petrov 1989; Chelli & Petrov 1995). More detailed modeling of the interferometric signal can also provide the inclination of the stellar rotation axis (Domiciano de Souza et al. 2004). This was partly our motivation to develop, in the framework of this thesis, the concept of an interferometric instrument which will be able to measure, next to other quantities of stars and circumstellar disks, the orientation of stellar rotation axes (Chapter 2).

For eclipsing binaries, however, one can obtain spatial information 'for free' since during the eclipse of one star by another different portions of the stellar disk are obscured at different times, providing an opportunity to resolve details on the surface of the eclipsed star. Particularly interesting in this respect is the Rossiter-McLaughlin (RM) effect (Rossiter 1924; McLaughlin 1924), a spectral distortion that is caused by the blockage of parts of the rotating stellar disk (see Figure 1.1). Due to the Doppler effect, light emitted from the side of the stellar disk that moves towards us is blueshifted and light emitted from the receding side is redshifted. When the redshifted (receding) part of the disk is blocked, the net starlight looks slightly blueshifted, and vice versa. If the spin axis of the eclipsed star is aligned with the orbital axis, first blueshifted light and later, to the same amount, redshifted light is blocked. For a misaligned axis this is not true, and redshifted and blueshifted light is blocked at different times and to different amounts. The RM effect has been known since 1924, but has not been exploited until recently because it is difficult to measure precisely and analyse quantitatively. For binary star systems this is partly because the absorption lines of the eclipsing foreground star blend the lines of the eclipsed background star. We will approach this challenge in Chapters 4 and 5 of this thesis.

1.1.3 Planets

The improvement of techniques originally developed for double star systems, in particular advances in the stability of Echelle spectrographs and analysis techniques, which made it possible to combine the signal of thousands of stellar absorption lines, have lead to the detection of the first extra solar planets around solar type stars (Mayor & Queloz 1995). Since the mid-1990s more than 300 planets have been detected. Via the measurement of Doppler shifts induced by the planetary companion, the orbital period of the planet, the eccentricity of its orbit and its minimum mass (the inclination of the orbit is not known) can be determined. More recently, also other techniques contributed to detections of planets such as micro-lensing, measurements of planetary transits, and recently also direct imaging of some massive planets around young stars.

The first planet for which a transit was measured was HD 209458b (Charbonneau et al. 2000). As for stellar eclipse measurements, transit measurements allow for the determination of the radius and mass, and therefore the density of the components. Now more than 40 transiting planets have been discovered and these measurements have shown, together with the Doppler measurements, that extrasolar planets are a very heterogeneous group with many surprising properties. For example it is believed that giant planets, such as Jupiter and Saturn, can only form at great distances from the parent stars, where ices are available in solid form to provide extra bulk to growing proto-planets. It was therefore a huge surprise to discover that $\sim$1% of Sun-like stars harbor a giant planet that orbits much closer than Mercury orbits the Sun. This finding has prompted major revisions in the theory of planet formation, mainly by allowing for 'migration' of planets to different orbits after they have formed (Lin et al. 1996). One class of migration theories invokes a tidal interaction between the planet and the disk of dust and gas from which it formed (e.g. Ida & Lin 2004). A second class of theories explains the migration by planet-planet gravitational scattering (e.g. Rasio & Ford 1996; Nagasawa et al. 2008) and a type of three-body interaction called the Kozai effect (Wu & Murray 2003).

The first theory, disk-planet migration, would leave the orbital spin axis aligned with the stellar spin axis, while the latter migration processes would produce misalignment. Hence, by measuring the degree of alignment between stellar and orbital axes one can distinguish between these theories. Researchers have begun to measure the relative orientation of the spin axes using the RM-effect (e.g. Winn et al. 2005). Recently, the first planetary system with a likely misalignment, XO-3, has been found (Hébrard et al. 2008). With the now rapidly growing sample of transiting planets, soon also planets with somewhat longer orbital periods, due to the space missions CoRoT and Kepler, the relative orientation of the stellar spin axis with respect to the orbital plane will be measured for a much larger sample, meaning that soon we might have a clearer picture about the formation history of these hot gas giants.

In addition, it has been found that some planets are inflated, i.e. their density is much lower than theory would predict (see Charbonneau et al. 2007, for a review). Is this a result of the intense stellar radiation these planets experience in their close orbits? Or might this be due to the tidal forces these planets experience in their possibly slightly eccentric orbits? While so far no clear route to solving the problem has appeared, measurements of the energy budget, by observing the eclipse of the planet by the star in the infrared (de Mooij & Snellen 2008), and observations of the brightness of the planet as a function of the planetary longitude (Knutson et al. 2007), might help to constrain possible theories. The measured orbital eccentricities for these planets themselves constitute another challenge for formation and evolution theories. For short-period planets, it is expected that eccentricities are quickly damped by tidal forces. Non-zero eccentricities may be caused by the presence of yet undiscovered planets in wider orbits.

The same group that observed the first planetary transit were first to detect signatures from this planet's atmosphere with transmission spectroscopy using STIS on HST (Charbonneau et al. 2002). Taking advantage of the stability and accuracy of this observatory, they could observe the transit depth with great precision in many different spectral bands. As planetary atmospheres absorb wavelength dependent, they could, for the first time, identify the signature of sodium. In the last chapter of this thesis I further develop techniques to observe extrasolar planets during transits, to make it possible to observe their atmospheres also using ground-based telescopes.

1.2 This thesis

In **Chapter 2** a novel instrumental concept is presented. It is shown that by coupling existing high-resolution spectrographs to existing interferometers, one can observe in the domain of high spectral and spatial resolution, and avoid the construction of a new complex and expensive instrument. We first show that this combination of high spatial and spectral resolution in optical astronomy would allow new observational approaches to many open problems in stellar and circumstellar astrophysics. The different challenges, which arise from combining an interferometer with a high-resolution spectrograph, are investigated. The requirements for the different sub-systems are determined, with special attention given to the problems of fringe tracking and dispersion in the interferometer. A concept study for the combination of the Very Large Telescope Interferometer (VLTI) with UV-Visual Echelle Spectrograph (UVES) is carried out, and several other specific instrument pairings are discussed. We show that the proposed combination of an interferometer with a high-resolution spectrograph is indeed feasible with current technology, for a small fraction of the cost of building a whole new spectrograph.

In **Chapter 3** observations and analysis of the massive young stellar object MWC 349A are presented, using the unique capabilities of the VLTI in combination with the Mid-Infrared Interferometric Instrument (MIDI) in N-band. The data can be modeled assuming a circumstellar disk consisting partly of amorphous silicates, and with a strong temperature gradient, as function of disk height above the mid-plane, out to a few hundred AU. The measurement of hydrogen recombination line masers in the visibility amplitudes and differential phases delivered by MIDI enabled us to create a simple model consisting of two emission regions located a few tens of AU away from the centre of the object. This agrees with what is found by earlier studies, that the hydrogen recombination lines originate in the atmosphere of the inner parts of the circumstellar disk. The simultaneous observation of the continuum emission from the circumstellar disk and the observation of the hydrogen lines enables us to establish that there exists a small but significant offset in the location of the centroid of the continuum and the centre of the emission line region, something difficult to establish if the continuum and the masers are observed with different instruments at different times.

In **Chapter 4 and Chapter 5** we use high spectral resolution observations of stellar eclipses to obtain spatial resolution information on stellar surface scales. We developed new and robust modeling tools to analyse the spectral distortion of stellar absorption lines during the eclipses, caused by the Rossiter–McLaughlin (RM) effect, which disentangle the light from the eclipsing foreground star and the light of the eclipsed background star.

For the eclipsing binary system V1143Cyg, which was observed at the Lick Observatory using the Hamilton high-resolution Echelle spectrograph, it is shown in **Chapter 4** that the rotation axes of the two stars are aligned with respect to each other and with the orbital axis, to within a few degrees, with the angle of the primary rotation axis $\beta_p = 0.3 \pm 1.5°$, and the angle of the secondary rotation axis $\beta_s = -1.2 \pm 1.6°$.

In **Chapter 5** we present our results for the binary system DI Herculis, which we observed with the Sophie high-resolution Echelle spectrograph on the Observatoire de Haute Provence. Our results show that the spin axes of both stars are tilted with respect to the orbital axis. The angle between the projected stellar spin axes and the projected orbital spin axis is $\beta_p = 71 \pm 4°$ for the primary and $\beta_s = 93 \pm 8°$ for the secondary. This is, to our knowledge, the first clear demonstration of such a strong misalignment in a close binary system. It solves a 20-year-old mystery about this system: the observed orbital precession is too slow to be in agreement with the predictions of general relativity (Moffat 1984, Claret 1998). This prediction was based on the premise of co-aligned stars. When this assumption is relaxed the paradox disappears. These results are not only important for the DI Herculis system but also for the formation and evolution theories of binary stars in general, since it is unclear how this system has formed and evolved this way.

In the final chapter of this thesis (**Chapter 6**) we present our results on ground-based transmission spectroscopy of the planetary atmosphere of HD 209458b. It is shown that transmission spectroscopy can be done routinely from the ground, possibly also for planets around less bright stars than HD 209458. The obtained spectra are corrected for instrumental effects, which influence the transmission spectroscopy, such as a change of the blaze function of the spectrograph, and a non-linearity effect in the CCD. Furthermore, methods have been developed to remove the influence of telluric sodium absorption, and absorption due to water in earth's atmosphere for spectra obtained under less than ideal weather conditions. We detect sodium in the atmosphere of HD 209458b and our measurements are fully consistent with earlier results. We further extend these observations by measuring the ratio between the Na D_2 and Na D_1 lines to be ~ 1.8. Around the centre of the transit the planetary sodium absorption seems to be less deep than during the rest of the transit, of which a hint is also seen in the Snellen et al. (2008) data. If real, this could be caused by the change in the relative radial velocity of the planet with respect to that of the star, with the planet's absorption centred at the centre of the stellar absorption line during mid-transit. Furthermore, a change in the shape of the stellar absorption line from centre to limb might contribute to this effect. For the absorption by potassium in the atmosphere of HD 209458b, we find an upper 3-σ limit of 0.042% in a passband of 1.5 Å.

1.3 Summary and outlook

In this thesis we use different techniques to investigate stars and planets at high spatial and spectral resolution. In Chapter 2 of this thesis we describe a fast and cost-effective way to combine high-resolution spectroscopy with optical interferometry, by connecting an existing interferometer to an existing spectrograph. We also show in which research fields such an instrument will be particularly useful. The first results delivered by the Astronomical Multiple BEam Recombiner (AMBER) instrument at the VLTI, with a spectral resolution of R $\sim$ 12 000 in the near-infrared shows the great potential such an instrument could have. Currently the Vega (Visible spEctroGraph and polArimeter) project is under construction with a spectral resolution of R $\sim$ 30 000 at the Chara array, which is expected to deliver fascinating new results. However, both instruments have a bandpass of a few tens of nanometers. To use cross correlation techniques, which have proven very useful for optical spectroscopy, a wider bandpass is needed. In this way one would have the same observing possibilities for different areas on stellar surfaces as one has now for the integrated light form the stellar surface as a whole, albeit at the moment only for bright stars.

In Chapters 4 and 5 two studies are presented in which high spectral resolution instruments are used, and by which the high spatial resolution is achieved by taking advantage of the occurrence of eclipses (Rossiter-McLaughlin effect).

In Chapter 4 the relative orientation of the stellar rotation axes of the binary system V1143 Cyg are studied. Analysis tools are developed to disentangle the light coming from the foreground eclipsing star and from the eclipsed background star. In this way it is possible to achieve spatial resolution on sub-stellar surface scales across stellar absorption lines. The two analysis tools developed in this work, in particular the method which incorporates the shape change of the stellar absorption line, and not only the change of centre of gravity, will enable the direct measurement of a number of stellar parameters difficult to access otherwise. It will be possible to accurately disentangle between rotational broadening and broadening due to velocity fields on the stellar surface and possible differential rotation. High signal-to-noise spectra obtained during eclipses will enable us to calculate limb darkening coefficients, not only for wavelength bands, but also over stellar absorption lines. i.e. It may be possible to establish the difference in stellar lines forming at the limb of the stellar disk and the centre. The subsequent blocking of the central and limb parts of the eclipsed star makes it relatively straight forward to remove the broadening of the stellar lines due to rotation, and to effectively obtain spectra of the limb and centre of the eclipsed star at different times.

In Chapter 5 we use the newly developed tools to derive the relative orientation of the spin axes in the DI Herculis system. We find that there exists a strong misalignment between the stellar spin axes and the orbital spin. This brings the expected apsidal motion in agreement with the measured apsidal motion, but it raises new questions: How did DI Herculis obtain its misaligned axes? Was it ‘formed’ with misaligned axes, and if so, how did it maintain this misalignment during the pre-main sequence phase, during which tidal forces are stronger due to greater radii of the components? Or did this young system acquire its current state during an subsequent evolution by multi-body interaction? Was it ejected from a cluster, or did Kozai migration, via an undiscovered third body in the system, lead to its current state?

A second connected class of interesting questions raised by the presented results in Chapter 5 are connected to the question whether systems like DI Herculis, with misaligned angular momentum vectors, are rare or common. If more systems with misaligned axes exist, then it would be instructive to know whether this misalignment is a function of orbital period, orbital eccentricity, and/or the total mass and mass ratio in the system. These measurements would help to refine theories of star formation as they basically provide constraints on an observable so far unobtained for non-contact binaries. There have been measurements of the inclination of stellar spin axes in RS CVn type binaries which suggest some degree of misalignment in these systems (Glebocki & Stawikowski 1997), but there were also suggestions that binaries with semi-major axes $\lesssim 40$ AU all have their spin vectors aligned (e.g. Hale 1994). So far we are missing information to answer the questions pointed out above.

To measure the orientation of a stellar spin axis, the stellar disk needs to be spatially resolved. An instrument presented in chapter 2, which would be able to measure the orientation of stellar spin axes for a variety of stars along the main sequence, is not available yet. One can, however, exploit for short-period systems the RM-effect during eclipses, and for long-period systems one can use the AMBER instrument at the VLTI. With a spectral resolution of R $\sim 12\,000$ in the near-infrared one would be able to use the Brγ line to determine the orientation axes in O and B stars. It would be particularly interesting to do so for stars of the Sco OB2 association, also to measure a possible alignment of single stars in the association.

Our measurements of the atmosphere of the exoplanet HD 209458b, presented in Chapter 6, using a ground-based telescope are interesting for two important reasons. We extend earlier measurements of the atmosphere by targeting the two Na D lines separately and by setting an upper limit to potassium absorption in the atmosphere of HD 209458b. Secondly, our measurements are completely consistent not only with the earlier HST results, but also with data taken with a different telescope and a different spectrograph under different weather conditions (Snellen et al. 2008). This shows that reliable measurements of extrasolar planet atmospheres are possible with ground-based telescopes. Now is the time to extend these measurements to different wavelengths, e.g. in the near infrared and to planets around less bright host stars.

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