PROCEEDINGS OF SCIENCE

Exoplanets

Simon Albrecht*
Massachusetts Institute of Technology, Kavli Institute for Astrophysics and Space Research, Cambridge, MA 02139, USA
E-mail: albrecht@space.mit.edu

In this paper I will discuss the current knowledge we have on planets orbiting other stars than our sun: exoplanets. Our ability to learn about exoplanets depends on the method we choose to search for them. Therefore I will give a short overview of the different detection techniques that are used to find planets. Special emphasis is placed on two techniques, radial velocity search and transit search.
I will also focus on a long standing riddle of the field: The occurrence of gas giant planets on orbits with periods of only a few days (Hot-Jupiters). These planets are similar to Jupiter but orbit their stars much closer than even Mercury orbits our own sun. The detection of these Hot-Jupiters was a surprise, as it is thought that they cannot form so close to their stars. Recent measurements of the Rossiter-McLaughlin effect helped to shed light on the formation and evolution of these systems.

Finally I will highlight some exciting new developments and recent detections of exoplanets in extreme environments.

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1. Introduction

Until the first exoplanet was detected around a sunlike star in 1995, only one planetary system had been available for study: our own. The theories that explained how planets formed out of a disk with smaller rocky planets closer in and gas giants further out could not be tested on new data. There was no way to know how common our type of system was or even if planets were common at all. By the close of 2011, about 600 exoplanets had been discovered, and even though there are biases as to what kinds of planets we can detect, interesting patterns have emerged, that shed new light on the main questions in the field.

We are on our way to finding out which other stars have planets and to what extent the architecture of these systems is similar to the solar system. We are constantly improving our understanding of planet formation, and are getting the first information on planetary atmospheres. There is an ongoing search for planets that are very similar to Earth and may be able to support life.

Our ability to learn about exoplanets depends on the method we choose to search for them. Therefore this paper will begin with an overview of the different detection techniques that are used to find planets. Special emphasis is placed on two techniques, radial velocity search and transit search.

In section 3 we will highlight one of the challenges to our current understanding of (exo)planet formation: the occurrence of Hot-Jupiters, gas giants on orbits around main sequence stars with orbital periods of only a few days. We will look into the progress which has been made in explaining these. We focus on evidence which comes from an until recently seldomly measured observable in astronomy: the angle between the orbital and rotational angular momentum of the stellar body. The Kepler observatory delivered some very exciting new results over the last months and we will highlight a few of these in section 4 before closing with an outlook in section 5.

This short review cannot possibly cover all the knowledge which has been accumulated over the last few years in the field of exoplanets. Good sources of information are the textbooks edited by Seager[42] and written by Perryman [33].

2. Detection techniques for extra solar planets

2.1 Radial velocity

Due to the gravitational pull of a planet on its host star, the orbit of the planet is mirrored in a much smaller movement in the star. The star makes a tiny orbit around the common center of mass of the star–planet system, which can be located inside the star. The component of this stellar wobble along the line of sight manifests itself in the form of a blueshift of the stellar absorption lines when the star is moving towards us and a redshift when it is moving away from us. The amount of displacement of the stellar absorption lines, measured with a spectrograph, lets us compute the radial velocity (RV) of the star. The amplitude (K) of these RV changes depends on the orbital period (P), and the eccentricity (e) of the orbit. It increases with the mass of the unseen planet ($M_{\rm p}$), and decreases with the mass of the star ($M_\star$) (e.g [13]);

$$K = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_{\rm p}\sin i_{\rm o}}{M_\star + M_{\rm p}} \frac{1}{(1-e^2)^{1/2}}. \tag{2.1}$$

Here i_o indicates the inclination of the orbit, where an inclination of 90° indicates an edge-on orbit with the observer located within the orbital plane of the planet. Equation 2.1 shows that to obtain the mass of an exoplanet, the mass of the host star needs to be estimated from stellar modeling. For non transiting planets the orbital plane is not known; only the minimum mass of the planet can be estimated. This is similar to the situation one encounters for single lined binary systems, where only the radial velocity of one star can be measured. If radial velocities of both stars can be measured, a double lined binary, and the system shows eclipses then the mass of both components can be measured independently of any model assumptions. These measurements are important to calibrate models of stellar structure and evolution [48]. In rare cases the radial velocity of an exoplanet can also be obtained directly, leading to a model-independent measurement of the masses in that system [44].

Due to the great difference between planetary and stellar mass, the amplitudes of the RV changes are small in exoplanet systems. For Jupiter the maximum amplitude of the RV signal would be 12.5 $\mathrm{m\,s^{-1}}$ and it would be as small as 0.09 $\mathrm{m\,s^{-1}}$ for the Earth. With

$$\frac{V_r}{v} = \frac{\Delta\lambda}{\lambda} \quad \text{for} \quad V_r << c, \tag{2.2}$$

where c indicates the speed of light, V_r the radial velocity of the star, λ the measurement wavelength, and $\Delta\lambda$ the shift in wavelength; this translates into small shifts in positions of stellar absorption lines. Techniques to measure these small shifts therefore measure not only the position of a single stellar absorption line but all the absorption lines in a large spectral window. Commonly a window between $\sim$ 400 nm and $\sim$ 700 nm is used depending on the particular technique applied. One technique uses a mask, nowadays a software mask, for cross-correlation with the stellar absorption line spectrum [18, 4, 35]. A single very high SNR line of which the shift can be measured with high accuracy is obtained. In another approach the light of the star passes through a gas absorption cell just before entering the slit of the spectrograph, imprinting the absorption of this particular gas on the stellar spectrum. In effect this multiplies the stellar spectrum by the gas spectrum. These observations are then compared to a combination of 1) a stellar spectrum observed without the gas cell and 2) a spectrum only containing absorption lines of the gas. The radial velocity of the star at a given observation is found by combining the gas cell spectrum with the clean stellar spectrum and applying a RV shift between the two. The RV which give the best fit represents the measured RV [7, 27].

The first exoplanet orbiting a sunlike star, 51 Pegasi, was detected via radial velocity measurements [29]. 51 Peg b orbits its host star in only 4.2 days and creates periodical radial velocity changes in its host star with an amplitude of 59 $\mathrm{m\,s^{-1}}$. The current limit on the precision of radial velocity is about $\sim 0.5\,\mathrm{m\,s^{-1}}$ and programs are under way to further improve this accuracy [26].

2.2 Photometry

Occasionally we are able to observe a solar eclipse, when the moon moves between the sun and the observer. If a celestial body occults only a smaller part of the sun, like Venus will do June 5/6, 2012, only small parts of the solar surface will be blocked from view, leading to a small reduction of overall flux from the sun during the time Venus transits in front of the sun (Figure 2.2).

When the line of sight towards a star hosting a planet coincides with the orbital plane of the planet, then every time the planet travels in front of its host star a small part of the disk would

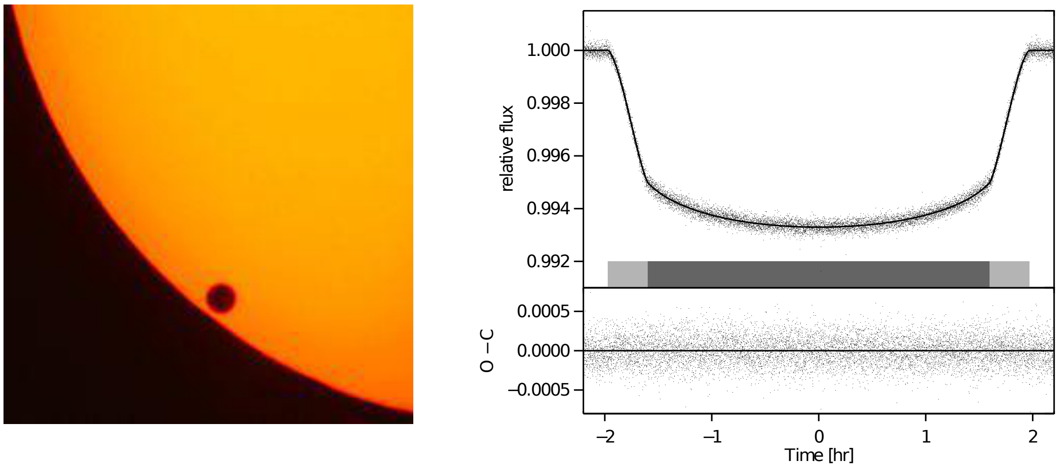

Figure 1: Transit Photometry *Left:* Transit of Venus 2004. Picture obtained from: `http://en.wikipedia.org/wiki/Transit_of_Venus` *Right:* Light observed from the HAT-P-7 system before, during, and after HAT-P-7b transits in front of its host star. The data was obtained by the Kepler spacecraft during Q6. The upper panel shows the phase folded light curve of a few transits and the best fitting model. The gray bars indicate the times of first, second, third, and forth contact. At times of first and forth contact the two disks touch. Between second and third contact the planetary disk is completely in fornt of the stellar disk. The depth of a Venus transit would be much smaller than the HAT-P-7b transit, as Venus occults only about 0.1% of the sun.

be obscured from the view. By monitoring stars for periodical brightness changes exoplanets can be discovered. If a Jupiter sized planet would transit a solar type star, a reduction of about 1% in total light would be observed, while an earth sized planet transiting the same star would only lead to a reduction of about 10^{-4} in flux. The first exoplanet which was found to transit its host star is HD 209458b [20, 8]. This star was first found via a radial velocity search. Since then HATnet [3], OGLE [49], WASP [34], and XO [30] and other ground based surveys (see [33] for a more complete listing) have discovered over 100 planets.

Most of these planets transit their stars on short orbits of only a few days. This is a selection effect, the wider the planet orbits the lower the probability to see it transit. The probability that a planet with $R_{\rm p} \ll R_{\star}$, on a circular orbit ($e \equiv 0$) is seen in transit ($P_{\rm tra}$) or occultation ($P_{\rm occ}$) is

$$P_{\rm tra} = P_{\rm occ} = R_{\star}/a \approx 0.005 \frac{R_{\star}}{R_{\odot}} \left(\frac{\rm a}{\rm AU}\right)^{-1}, \tag{2.3}$$

for a circular orbit (equ. 11, [50]). Here $R_{\star}$ indicated the stellar radius, $R_{\odot}$ the radius of the sun and a the semi major axis and AU one astronomical unit. An observer at a random position outside the solar system would be able to see a transit of Earth in front of the sun with a probability of 0.5%. To actually observe a transit, the observations would have to take place around the 13 hours which the earth needs to cross the solar disk once a year. Therefore a ground based transit search, interrupted by daylight will only effectively find planets on orbits of a few days and will not be able find long period systems.

Surveying smaller and cooler M dwarfs for transits has the advantage that for the same planetary radii the depth of the transit is deeper, leading to the discovery of smaller planets with the same measurement precision. In addition, planets with relatively short periods will be located nearer the habitable zone of that star, defined by the distance from the host star where water is liquid. However, late type stars are intrinsically faint, leading to a low density of suitable search targets on the plane of the sky and the need to be targeted separately. The MEarth survey detected the 6.5 M_{Earth} planet GJ 1214b with this approach [9].

Continuous observations from a space-based observatory would increase the sensitivity towards smaller transit depths as variations in the earth's atmosphere do not corrupt the measurements. In addition the sensitivity towards planets with longer orbital periods would be increased as near continuous observations are possible. Recent results from the Kepler satellite are discussed in section 4.

2.3 Other techniques to search for exoplanets

There are a variety of other techniques to search for planets outside our own solar system. Each of these has particular advantages and disadvantages. We refer the reader to [42] and [33] for a more detailed overview and discuss them here only briefly:

- **Direct Imaging:** Obtaining photons from an exoplanet directly would enable the study of their atmospheres, important if we want to learn about the planets ability to host life. As the contrast ratios between planets and host stars are steep and the separations are small, this is at the same time also a very challenging method. If we were to observe the solar system from a distance of 10 pc, we would observe Jupiter at an angular distance of only 0.5 arcsec and with a contrast ratio of 10^{-9} in the visible. Therefore direct imaging surveys work in the near infrared where contrast ratios between the cold body, the planet, and the hot body, the star, are reduced. Surveys also often target young systems, where planets still emit gravitational energy from their formation. This way a few systems have been detected via direct imaging (e.g. [28]). With a new generation of dedicated instruments which are currently installed at different observatories, direct imaging might soon contribute to many new discoveries in exoplanet science. As direct imaging is sensitive to planets on wide orbits, a different planet population is probed than with previous methods.

- **Astrometry:** While with the radial velocity method we can measure velocity change along the line-of-sight, with astrometry measurements of stellar positions and their changes, projected on the sky, are measured. An unseen companion can cause both, changes in radial velocity and the projected position changes. While the radial velocity signal decreases with separation between the star and the planet the astrometric signal is proportional to the separation. This increased sensitivity towards companions on wider orbits, and the different sets of orbital parameters that are measured make astrometric observations complementary to the RV method. Using the fine guidance sensors on board *Hubble*, the astrometric signature of a few already known planets has been detected, and the masses of these non transiting planets have been determined. Benedict et al. 2006 [5] detected the astrometric signature of the planet orbiting ε Eridani. Using *Hipparcos* data, Reffert & Quirrenbach 2011 [37] have set upper mass limits on additional planets also found via the RV method. With the space-based GAIA mission [24] and the ESPRI planet search using the VLT Interferometer

[22], this method will likely deliver new planet detection around relatively nearby stars and will remove the ambiguity in the planetary mass of a number of already detected systems.

- **Microlensing:** If a star passes near the line of sight between the observer and a more distant background star, then multiple images of the background star are created. These images can not be separated and the light from the background star simply appears magnified. If the foreground star harbors a planet then additional substructure can be seen on the light curve of these microlensing events, enabling the detection of these lensing planets. This detection technique has some unique advantages and disadvantages and we refer the interested reader to [16] for a thorough review. One recent interesting result of microlensing surveys was the realization that our galaxy harbors many free floating planets [46].

- **Timing:** The first discovery of an exoplanet was achieved by timing the pulsar PSR B1257+12 [53]. The planets founds around this neutron star have masses of only a few earth masses. By carefully modeling the planetary orbits and their evolution the presence of a third planet, with a mass of 0.02 M_{Earth} was inferred. While planets around supernova remnants remain rare, the existence of only a few of these planets poses some interesting questions about planet formation and evolution. As we will see in section 4, the timing of eclipses and transits can also lead to the discovery of planetary companions.

3. Hot-Jupiters

3.1 Star and planet formation in a nutshell

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 center of these dense cores, a star begins to form. During this process it is thought that a circumstellar disk is formed by infalling material due to its non-zero angular momentum. Accretion from the disk onto the star is believed to drive bipolar 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.

The properties of the planetary systems discovered over the last years often have surprised us and challenged our paradigmata of planet formation and evolution. One of these surprises was the discovery of gas giant planets, like Jupiter, but on very close orbits leading to orbital periods of only a few days. The discovery of these Hot-Jupiters was a surprise, as it is believed that gas giants can form only at distances of a few AU behind the *snow line*. It is thought that only there enough solid material is present to rapidly form a solid proto-planet which acts as a seed for the gas giant.

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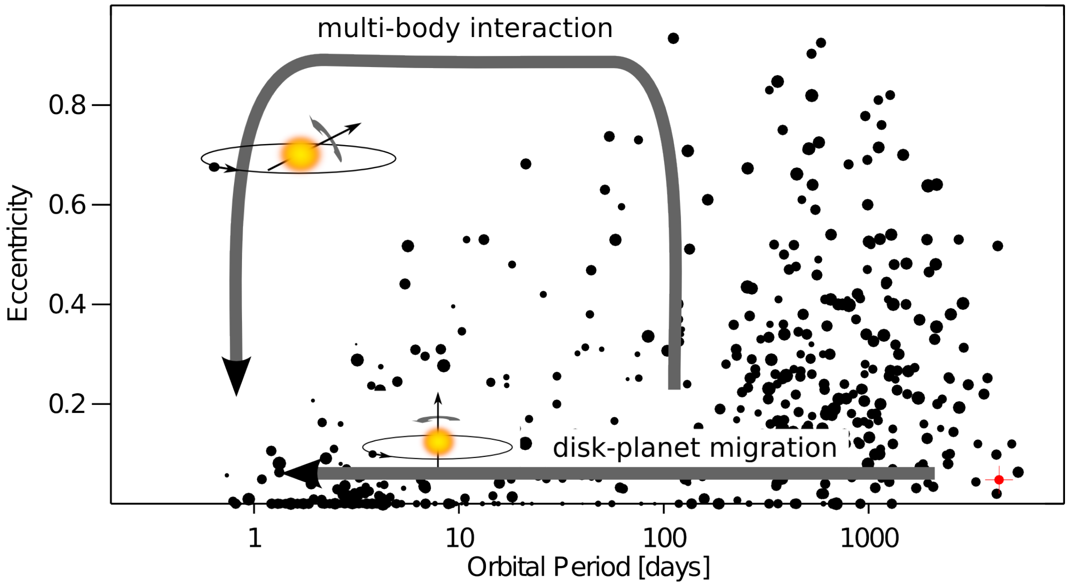

Figure 2: Migration of giant planets. Orbital period and eccentricity of 600 exoplanets. The size of the dots indicates the mass of the planets. The gas giant in the solar system with the shortest orbital period, Jupiter, is indicated by the red circle with a cross. Migration of the planet via an interaction with the disk would effect the orbital period but would not significantly change the orbital, eccentricity and inclination. A migration also involving multi body interaction, like planet-planet scattering or Kozai migration, would increase the orbital eccentricity and inclination. Orbital eccentricities eventually decrease for close systems. For star-planet systems the damping of obliquities might take much longer. This makes the stellar obliquity a good tracer of the migration history in these systems.

3.2 Migration of giant planets

Different classes of processes have been proposed which might transport giant planets from their presumed birthplaces at distances of many astronomical units from their host stars, inward to a fraction of an astronomical unit, where we find them. Some of these processes are expected to change the relative orientation between the stellar and orbital spin (e.g. [32, 15, 10]). These processes involve planet-planet scattering or Kozai migration. Migration via an interaction between the young planet and the disk out of which it formed would not change the orbital plane of the planet. Therefore, if good alignment between disk and stellar equator is assumed, then this migration would lead to a good alignment between the orbital and stellar angular momenta (e.g. [23]), or even reduce a misalignment between them [12]. Measuring stellar obliquities, the angle between the stellar rotation axis and orbital angular momentum, might therefore help to distinguish between different migration theories and improve our understanding of the formation and evolution of these systems (Figure 2).

3.3 Measuring stellar obliquities through the RM effect

The sun is the only star for which we can obtain detailed information on spacial scales much smaller than its diameter. For most stars, we are not able to resolve their surfaces. These stars are essentially point sources, even for the biggest telescopes.

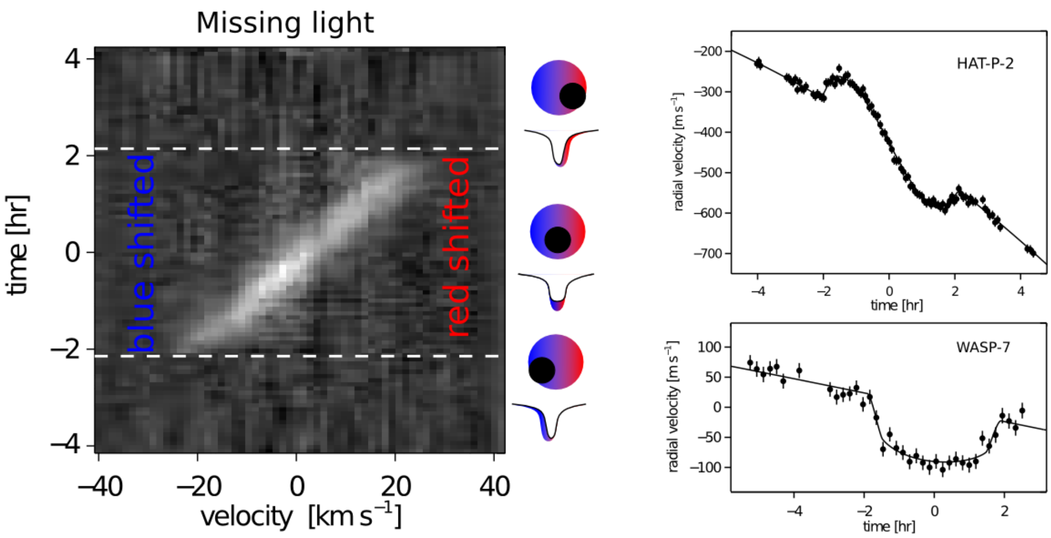

Figure 3: The Rossiter-McLaughlin effect. During the transit of a planet in front of its star different parts of the stellar absorption lines are hidden from view. The left panel shows this missing component during a transit in the HAT-P-2 system. At the beginning of the transit, parts of the approaching stellar surface area are hidden from you, blueshifted light is missing. At the end, red shifted light is missing. The RVs measured during this transit are shown in the upper left panel, where one can see the change in RV due to the orbital velocity and the RM effect. The lower left panel shows the RM effect in the WASP-7 system, where the stellar rotation is by $\sim 90^{\circ}$ titled agains the orbital angular momentum [2].

A transit of an exoplanet over the disk of its host star can provide us with an opportunity to obtain high spatial resolution. During transits, telescopes integrate not over the complete stellar disk, as parts are hidden from view. Already Holt 1893 [21] realized that, for the case of eclipsing double stars, this is an opportunity to measure the projected stellar rotation speed ($v \sin i_{\star}$) independently from a measurement of the width of the absorption lines. Stellar lines are broadened by the Doppler shift due to rotation. Light emitted from approaching stellar surface areas is blue shifted and light emitted from receding stellar surface areas is red shifted. During eclipse parts of the rotating stellar surface is hidden, causing a weakening of the corresponding velocity component of the stellar absorption lines. Modeling of this spectral distortion reveals $v \sin i_{\star}$ and the angle between the stellar and orbital spins projected on the plane of the sky: the projected obliquity (see Figure 3).

A claim of the detection of the rotation anomaly was made by Schlesinger 1910 [41], but more definitive measurements were achieved by Rossiter 1924 [38] and McLaughlin1924 [31] for the β Lyrae and Algol systems, respectively. These researchers reported the change of the first moment of the absorption lines, sometimes called center of gravity, derived form the shape of the absorption line. Struve 1931[45] reported the shape and its change during eclipse in the Algol system. The phenomenon is now known as the Rossiter-McLaughlin (RM) effect.

3.4 Results for obliquities in extrasolar planetary systems

The first measurement of a projected obliquity in an extrasolar system was made by Queloz et al. 2000 [36]. They found that HD 209458 has a low obliquity. Over the following years the angle between the stellar and orbital spins have been measured in about 30 systems. It was found that for some of these systems the orbits are inclined or even retrograde with respect to the rotational spins of their host stars [19, 51, 43, 1].

Winn et al. 2010 [52] found that close-in giant planets tend to have orbits aligned with the stellar spin if the effective temperature ($T_{\rm eff}$) of their host star is $\lesssim 6250$ K and misaligned otherwise. Schlaufman 2010[40] obtained similar results measuring the inclination of spin axes along the line of sight. Winn et al. 2010 [52] further speculated that this might indicate that *all* giant planets are transported inward by processes which randomize the obliquity. In this picture tidal waves raised on the star by the close-in planet realign the two angular momentum vectors. The realignment time scale would be short for planets around stars with convective envelopes ($T_{\rm eff} \lesssim 6250$ K), but long, compared to the lifetime of the system, if the star does not have a convective envelope ($T_{\rm eff} \gtrsim 6250$ K).

Over the last $1\frac{1}{2}$ years the number of systems with measured projected obliquities nearly doubled and the predictions made by Winn et al. 2010 [52] have been confirmed for these systems (see Figure 4) lending support to the idea that systems with close giant planets generally started out with a very broad range of obliquities, and that the observed low obliquities of many systems are a consequence of tidal dissipation. Assuming that the protoplanetary disks are aligned with the stellar equator, this points to a migration path which involves, next to disk-planet interactions, also scattering processes or Kozai migration, changing the orbital plane of the planet.

It would be educational to measure obliquities also in systems with smaller planets, planets on wider orbits, and systems with multiple planets. The *Kepler* satellite provides us with these kind of systems, and measurements of obliquities in these systems are underway.

4. Kepler

The *Kepler* observatory was launched March 6, 2009 into an earth trailing orbit. It has a modified Schmidt telescope with 0.95 m of effective aperture. The light from 115 square degree on the sky is focused on an array of 42 CCDs [6], enabling the near continuous monitoring of the light of $\sim 150\,000$ stars in the constellation of Cygnus over mission time of Kepler.

The main goal of Kepler is to determine the frequency of Earth sized planets in the habitable zones of Sun-like stars (η-Earth). In its now nearly three years in space it has discovered a number of new types of planetary systems and lead to some interesting results in astronomy which would not have been possible otherwise. I list here a short and subjective selection.

- Kepler has found hundreds of systems with multiple transiting planets. The current record holder is the Kepler-11 system which harbors 6 transiting planets [25]. These planets have mutual inclinations of less then 0.6° and all orbit their sun-like host star on orbits with smaller semi-major axes than Venus the sun.

- In systems with multiple planets, the planets do not only move in the gravitational field of their host star, but their orbits are also influenced by the gravitation of the other planets. This

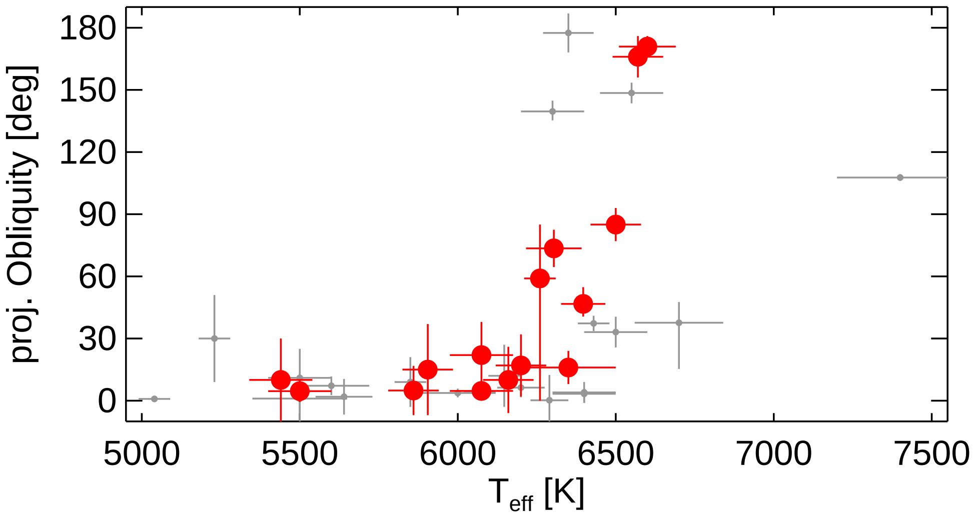

Figure 4: Hotter stars have oblique rotation. The projected obliquity of Hot Jupiter ($M_{planet} > 0.2\ M_{Jupiter}$; Period < 6 days) systems is plotted as function of the effective temperature of the host star. Using measurements available at that time, [52] noticed that systems with cool stars are aligned, while the obliquities of hot stars tends to be higher (gray small circles). Since then 16 new RM measurements have been reported (red large circles.

modulation of the orbits is most readily seen as variations in the times the planets transit in front of their host stars. These transit timing variations (TTV) provide us with an elegant way to derive the masses of the perturbing planets (e.g. [11]).

- While many planets have been detected around single stars or orbiting a single members of wide ($>$ 20 AU) double star systems, planets orbiting two stars have until recently been elusive. Doyle et al. 2011 [14] announced that the two stars in the Kepler-16 system, which orbit each other every 41 days, have a Saturn like companion in a 229 day orbit around both stars.

- Kepler also opens the opportunity to measure stellar obliquities without the need of dedicated spectroscopic observations. For slowly rotating stars the crossing of star-spots can be used as a tracer of stellar obliquity (e.g. [39]). For rapidly rotating stars which exhibit gravity darkening, the projected obliquity can be estimated from high quality photometry [47].

- Modeling stellar interiors and characteristics via asteroseismology also benefits from the long duration, high precision light curves obtained by Kepler [17]. The results obtained this way are not only very interesting by themselves, they will also lead to better constrains on planetary parameters. The later often depend on stellar parameters. for example the measured value for the absolute radius of the planet depends on the measurement of the stellar radius, which in turn can be obtained via asteroseismology.

5. Outlook

Unearthing the treasure trove of Kepler data has just begun and more discoveries are probably to come. In addition new photometric missions are in the planning stage (e.g. TESS). Improvements of techniques like direct imaging and RV should lead in the near future to discoveries of more alien worlds different from (exo)planets we know so far.

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References

[1] Albrecht, S., Winn, J. N., Johnson, J. A., Butler, R. P., Crane, J. D., Shectman, S. A., Thompson, I. B., Narita, N., Sato, B., Hirano, T., Enya, K., & Fischer, D. (2011). *Two Upper Limits on the Rossiter-Mclaughlin Effect, with Differing Implications: WASP-1 has a High Obliquity and WASP-2 is Indeterminate*. ApJ, **738**, 50.

[2] Albrecht, S., Winn, J. N., Butler, R. P., Crane, J. D., Shectman, S. A., Thompson, I. B., Hirano, T., & Wittenmyer, R. A. (2012). *A High Stellar Obliquity in the WASP-7 Exoplanetary System*. ApJ, **744**, 189.

[3] Bakos, G. Á., Lázár, J., Papp, I., Sári, P., & Green, E. M. (2002). *System Description and First Light Curves of the Hungarian Automated Telescope, an Autonomous Observatory for Variability Search*. PASP, **114**, 974.

[4] Baranne, A., Mayor, M., & Poncet, J. L. (1979). *CORAVEL - A new tool for radial velocity measurements*. Vistas in Astronomy, **23**, 279.

[5] Benedict, G. F., McArthur, B. E., Gatewood, G., Nelan, E., Cochran, W. D., Hatzes, A., Endl, M., Wittenmyer, R., Baliunas, S. L., Walker, G. A. H., Yang, S., Kürster, M., Els, S., & Paulson, D. B. (2006). *The Extrasolar Planet ε Eridani b: Orbit and Mass*. AJ, **132**, 2206.

[6] Borucki, W. J., Koch, D., Basri, G., Batalha, N., Brown, T., Caldwell, D., Caldwell, J., Christensen-Dalsgaard, J., Cochran, W. D., DeVore, E., Dunham, E. W., Dupree, A. K., Gautier, T. N., Geary, J. C., Gilliland, R., Gould, A., Howell, S. B., Jenkins, J. M., Kondo, Y., Latham, D. W., Marcy, G. W., Meibom, S., Kjeldsen, H., Lissauer, J. J., Monet, D. G., Morrison, D., Sasselov, D., Tarter, J., Boss, A., Brownlee, D., Owen, T., Buzasi, D., Charbonneau, D., Doyle, L., Fortney, J., Ford, E. B., Holman, M. J., Seager, S., Steffen, J. H., Welsh, W. F., Rowe, J., Anderson, H., Buchhave, L., Ciardi, D., Walkowicz, L., Sherry, W., Horch, E., Isaacson, H., Everett, M. E., Fischer, D., Torres, G., Johnson, J. A., Endl, M., MacQueen, P., Bryson, S. T., Dotson, J., Haas, M., Kolodziejczak, J., Van Cleve, J., Chandrasekaran, H., Twicken, J. D., Quintana, E. V., Clarke, B. D., Allen, C., Li, J., Wu, H., Tenenbaum, P., Verner, E., Bruhweiler, F., Barnes, J., & Prsa, A. (2010). *Kepler Planet-Detection Mission: Introduction and First Results*. Science, **327**, 977.

[7] Campbell, B. & Walker, G. A. H. (1979). *Precision radial velocities with an absorption cell*. PASP, **91**, 540.

[8] Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. (2000). *Detection of Planetary Transits Across a Sun-like Star*. ApJ, **529**, L45.

[9] Charbonneau, D., Berta, Z. K., Irwin, J., Burke, C. J., Nutzman, P., Buchhave, L. A., Lovis, C., Bonfils, X., Latham, D. W., Udry, S., Murray-Clay, R. A., Holman, M. J., Falco, E. E., Winn, J. N., Queloz, D., Pepe, F., Mayor, M., Delfosse, X., & Forveille, T. (2009). *A super-Earth transiting a nearby low-mass star*. Nature, **462**, 891.

[10] Chatterjee, S., Ford, E. B., Matsumura, S., & Rasio, F. A. (2008). *Dynamical Outcomes of Planet-Planet Scattering*. ApJ, **686**, 580.

[11] Cochran, W. D., Fabrycky, D. C., Torres, G., Fressin, F., Désert, J.-M., Ragozzine, D., Sasselov, D., Fortney, J. J., Rowe, J. F., Brugamyer, E. J., Bryson, S. T., Carter, J. A., Ciardi, D. R., Howell, S. B., Steffen, J. H., Borucki, W. J., Koch, D. G., Winn, J. N., Welsh, W. F., Uddin, K., Tenenbaum, P., Still, M., Seager, S., Quinn, S. N., Mullally, F., Miller, N., Marcy, G. W., MacQueen, P. J., Lucas, P., Lissauer, J. J., Latham, D. W., Knutson, H., Kinemuchi, K., Johnson, J. A., Jenkins, J. M., Isaacson, H., Howard, A., Horch, E., Holman, M. J., Henze, C. E., Haas, M. R., Gilliland, R. L., Gautier, III, T. N., Ford, E. B., Fischer, D. A., Everett, M., Endl, M., Demory, B.-O., Deming, D., Charbonneau, D., Caldwell, D., Buchhave, L., Brown, T. M., & Batalha, N. (2011). *Kepler-18b, c, and d: A System of Three Planets Confirmed by Transit Timing Variations, Light Curve Validation, Warm-Spitzer Photometry, and Radial Velocity Measurements*. ApJS, **197**, 7.

[12] Cresswell, P., Dirksen, G., Kley, W., & Nelson, R. P. (2007). *On the evolution of eccentric and inclined protoplanets embedded in protoplanetary disks*. A&A, **473**, 329.

[13] Cumming, A., Marcy, G. W., & Butler, R. P. (1999). *The Lick Planet Search: Detectability and Mass Thresholds*. ApJ, **526**, 890.

[14] Doyle, L. R., Carter, J. A., Fabrycky, D. C., Slawson, R. W., Howell, S. B., Winn, J. N., Orosz, J. A., Prcaronsa, A., Welsh, W. F., Quinn, S. N., Latham, D., Torres, G., Buchhave, L. A., Marcy, G. W., Fortney, J. J., Shporer, A., Ford, E. B., Lissauer, J. J., Ragozzine, D., Rucker, M., Batalha, N., Jenkins, J. M., Borucki, W. J., Koch, D., Middour, C. K., Hall, J. R., McCauliff, S., Fanelli, M. N., Quintana, E. V., Holman, M. J., Caldwell, D. A., Still, M., Stefanik, R. P., Brown, W. R., Esquerdo, G. A., Tang, S., Furesz, G., Geary, J. C., Berlind, P., Calkins, M. L., Short, D. R., Steffen, J. H., Sasselov, D., Dunham, E. W., Cochran, W. D., Boss, A., Haas, M. R., Buzasi, D., & Fischer, D. (2011). *Kepler-16: A Transiting Circumbinary Planet*. Science, **333**, 1602.

[15] Fabrycky, D. & Tremaine, S. (2007). *Shrinking Binary and Planetary Orbits by Kozai Cycles with Tidal Friction*. ApJ, **669**, 1298.

[16] Gaudi, B. S. (2010). *Exoplanetary Microlensing*. ArXiv e-prints.

[17] Gilliland, R. L., Brown, T. M., Christensen-Dalsgaard, J., Kjeldsen, H., Aerts, C., Appourchaux, T., Basu, S., Bedding, T. R., Chaplin, W. J., Cunha, M. S., De Cat, P., De Ridder, J., Guzik, J. A., Handler, G., Kawaler, S., Kiss, L., Kolenberg, K., Kurtz, D. W., Metcalfe, T. S., Monteiro, M. J. P. F. G., Szabó, R., Arentoft, T., Balona, L., Debosscher, J., Elsworth, Y. P., Quirion, P.-O., Stello, D., Suárez, J. C., Borucki, W. J., Jenkins, J. M., Koch, D., Kondo, Y., Latham, D. W., Rowe, J. F., & Steffen, J. H. (2010). *Kepler Asteroseismology Program: Introduction and First Results*. PASP, **122**, 131.

[18] Griffin, R. F. (1967). *A Photoelectric Radial-Velocity Spectrometer*. ApJ, **148**, 465.

[19] Hébrard, G., Bouchy, F., Pont, F., Loeillet, B., Rabus, M., Bonfils, X., Moutou, C., Boisse, I., Delfosse, X., Desort, M., Eggenberger, A., Ehrenreich, D., Forveille, T., Lagrange, A., Lovis, C., Mayor, M., Pepe, F., Perrier, C., Queloz, D., Santos, N. C., Ségransan, D., Udry, S., & Vidal-Madjar, A. (2008). *Misaligned spin-orbit in the XO-3 planetary system?* A&A, **488**, 763.

[20] Henry, G. W., Marcy, G., Butler, R. P., & Vogt, S. S. (1999). *HD 209458*. IAU Circ., **7307**, 1.

[21] Holt, J. R. (1893). *Spectroscopic Determination of Stellar Rotation*. A&A, **12**, 646.

[22] Launhardt, R. (2009). *Exoplanet search with astrometry*. New A Rev., **53**, 294.

[23] Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. (1996). *Orbital migration of the planetary companion of 51 Pegasi to its present location*. Nature, **380**, 606.

[24] Lindegren, L., Babusiaux, C., Bailer-Jones, C., Bastian, U., Brown, A. G. A., Cropper, M., Høg, E., Jordi, C., Katz, D., van Leeuwen, F., Luri, X., Mignard, F., de Bruijne, J. H. J., & Prusti, T. (2008). *The Gaia mission: science, organization and present status*. In W. J. Jin, I. Platais, & M. A. C. Perryman, editor, IAU Symposium, volume 248 , 217.

[25] Lissauer, J. J., Fabrycky, D. C., Ford, E. B., Borucki, W. J., Fressin, F., Marcy, G. W., Orosz, J. A., Rowe, J. F., Torres, G., Welsh, W. F., Batalha, N. M., Bryson, S. T., Buchhave, L. A., Caldwell, D. A., Carter, J. A., Charbonneau, D., Christiansen, J. L., Cochran, W. D., Desert, J.-M., Dunham, E. W., Fanelli, M. N., Fortney, J. J., Gautier, III, T. N., Geary, J. C., Gilliland, R. L., Haas, M. R., Hall, J. R., Holman, M. J., Koch, D. G., Latham, D. W., Lopez, E., McCauliff, S., Miller, N., Morehead, R. C., Quintana, E. V., Ragozzine, D., Sasselov, D., Short, D. R., & Steffen, J. H. (2011). *A closely packed system of low-mass, low-density planets transiting Kepler-11*. Nature, **470**, 53.

[26] Lovis, C. & Fischer, D. (2010). *Radial Velocity Techniques for Exoplanets*, 27.

[27] Marcy, G. W. & Butler, R. P. (1992). *Precision radial velocities with an iodine absorption cell*. PASP, **104**, 270.

[28] Marois, C., Macintosh, B., Barman, T., Zuckerman, B., Song, I., Patience, J., Lafrenière, D., & Doyon, R. (2008). *Direct Imaging of Multiple Planets Orbiting the Star HR 8799*. Science, **322**, 1348.

[29] Mayor, M. & Queloz, D. (1995). *A Jupiter-mass companion to a solar-type star*. Nature, **378**, 355.

[30] McCullough, P. R., Stys, J. E., Valenti, J. A., Fleming, S. W., Janes, K. A., & Heasley, J. N. (2005). *The XO Project: Searching for Transiting Extrasolar Planet Candidates*. PASP, **117**, 783.

[31] McLaughlin, D. B. (1924). *Some Results of a Spectrographic Study of the Algol System.* ApJ, **60**, 22.

[32] Nagasawa, M., Ida, S., & Bessho, T. (2008). *Formation of Hot Planets by a Combination of Planet Scattering, Tidal Circularization, and the Kozai Mechanism*. ApJ, **678**, 498.

[33] Perryman, M. (2011). *The Exoplanet Handbook*.

[34] Pollacco, D. L., Skillen, I., Collier Cameron, A., Christian, D. J., Hellier, C., Irwin, J., Lister, T. A., Street, R. A., West, R. G., Anderson, D., Clarkson, W. I., Deeg, H., Enoch, B., Evans, A., Fitzsimmons, A., Haswell, C. A., Hodgkin, S., Horne, K., Kane, S. R., Keenan, F. P., Maxted, P. F. L., Norton, A. J., Osborne, J., Parley, N. R., Ryans, R. S. I., Smalley, B., Wheatley, P. J., & Wilson, D. M. (2006). *The WASP Project and the SuperWASP Cameras*. PASP, **118**, 1407.

[35] Queloz, D. (1995). *Echelle Spectroscopy with a CCD at Low Signal-To-Noise Ratio*. In A. G. D. Philip, K. Janes, & A. R. Upgren, editor, New Developments in Array Technology and Applications, volume 167 of IAU Symposium, 221.

[36] Queloz, D., Eggenberger, A., Mayor, M., Perrier, C., Beuzit, J. L., Naef, D., Sivan, J. P., & Udry, S. (2000). *Detection of a spectroscopic transit by the planet orbiting the star HD209458*. A&A, **359**, L13.

[37] Reffert, S. & Quirrenbach, A. (2011). *Mass constraints on substellar companion candidates from the re-reduced Hipparcos intermediate astrometric data: nine confirmed planets and two confirmed brown dwarfs*. A&A, **527**, A140.

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[38] Rossiter, R. A. (1924). *On the Detection of an Effect of Rotation During Eclipse in the Velocity of the Brigher Component of Beta Lyrae, and on the Constancy of Velocity of this System.* ApJ, **60**, 15.

[39] Sanchis-Ojeda, R. & Winn, J. N. (2011). *Starspots, spin-orbit misalignment, and active latitudes in the HAT-P-11 exoplanetary system*. ArXiv: 1107.2920.

[40] Schlaufman, K. C. (2010). *Evidence of Possible Spin-orbit Misalignment Along the Line of Sight in Transiting Exoplanet Systems*. ApJ, **719**, 602

[41] Schlesinger, F. (1910). *The Algol-variable delta Librae*. *Publications of the Allegheny Observatory of the University of Pittsburgh*, **1**, 123.

[42] Seager, S. (2011). *Exoplanets*.

[43] Simpson, E. K., Pollacco, D., Cameron, A. C., Hébrard, G., Anderson, D. R., Barros, S. C. C., Boisse, I., Bouchy, F., Faedi, F., Gillon, M., Hebb, L., Keenan, F. P., Miller, G. R. M., Moutou, C., Queloz, D., Skillen, I., Sorensen, P., Stempels, H. C., Triaud, A., Watson, C. A., & Wilson, P. A. (2011). *The spin-orbit angles of the transiting exoplanets WASP-1b, WASP-24b, WASP-38b and HAT-P-8b from Rossiter-McLaughlin observations*. MNRAS, **414**, 3023.

[44] Snellen, I. A. G., de Kok, R. J., de Mooij, E. J. W., & Albrecht, S. (2010). *The orbital motion, absolute mass and high-altitude winds of exoplanet HD209458b*. Nature, **465**, 1049.

[45] Struve, O. & Elvey, C. T. (1931). *Algol and stellar rotation*. MNRAS, **91**, 663.

[46] Sumi, T., Kamiya, K., Bennett, D. P., Bond, I. A., Abe, F., Botzler, C. S., Fukui, A., Furusawa, K., Hearnshaw, J. B., Itow, Y., Kilmartin, P. M., Korpela, A., Lin, W., Ling, C. H., Masuda, K., Matsubara, Y., Miyake, N., Motomura, M., Muraki, Y., Nagaya, M., Nakamura, S., Ohnishi, K., Okumura, T., Perrott, Y. C., Rattenbury, N., Saito, T., Sako, T., Sullivan, D. J., Sweatman, W. L., Tristram, P. J., Udalski, A., Szymański, M. K., Kubiak, M., Pietrzyński, G., Poleski, R., Soszyński, I., Wyrzykowski, Ł., Ulaczyk, K., & Microlensing Observations in Astrophysics (MOA) Collaboration (2011). *Unbound or distant planetary mass population detected by gravitational microlensing*. Nature, **473**, 349.

[47] Szabó, G. M., Szabó, R., Benkő, J. M., Lehmann, H., Mező, G., Simon, A. E., Kővári, Z., Hodosán, G., Regály, Z., & Kiss, L. L. (2011). *Asymmetric Transit Curves as Indication of Orbital Obliquity: Clues from the Late-type Dwarf Companion in KOI-13*. ApJ, **736**, L4.

[48] Torres, G., Andersen, J., & Giménez, A. (2010). *Accurate masses and radii of normal stars: modern results and applications*. A&A Rev., **18**, 67.

[49] Udalski, A., Paczynski, B., Zebrun, K., Szymanski, M., Kubiak, M., Soszynski, I., Szewczyk, O., Wyrzykowski, L., & Pietrzynski, G. (2002). *The Optical Gravitational Lensing Experiment. Search for Planetary and Low-Luminosity Object Transits in the Galactic Disk. Results of 2001 Campaign*. Acta Astron., **52**, 1.

[50] Winn, J. N. (2010). *Transits and Occultations*. ArXiv: 1001.2010.

[51] Winn, J. N., Johnson, J. A., Albrecht, S., Howard, A. W., Marcy, G. W., Crossfield, I. J., & Holman, M. J. (2009). *HAT-P-7: A Retrograde or Polar Orbit, and a Third Body*. ApJ, **703**, L99.

[52] Winn, J. N., Fabrycky, D., Albrecht, S., & Johnson, J. A. (2010). *Hot Stars with Hot Jupiters Have High Obliquities*. ApJ, **718**, L145.

[53] Wolszczan, A. & Frail, D. A. (1992). *A planetary system around the millisecond pulsar PSR1257 + 12*. Nature, **355**, 145.