Exoplanets, 2003 – 2013

Gáspár Áron Bakos

Abstract: Cosmologists and philosophers had long suspected that our sun was a star, and that just like the sun, other stars were also orbited by planets. These and similar ideas led to Giordano Bruno being burned at the stake by the Roman Inquisition in 1600. It was not until 1989, however, that the first exoplanet – a planet outside the solar system – was discovered. While the rate of subsequent discoveries was slow, most of these were important milestones in the research on extrasolar planets, such as finding planets around a pulsar (a compact remnant of a collapsed star) and finding Jupiter-mass planets circling their stars on extremely short period orbits (in less than a few Earth-days). But the first decade of our millennium witnessed an explosion in the number of discovered exoplanets. To date, there are close to one thousand confirmed and three thousand candidate exoplanets. We now know that a large fraction of stars have planets, and that these planets show an enormous diversity, with masses ranging from that of the moon (1/100 that of Earth, or 0.01$M_{\oplus}$) to twenty-five times that of Jupiter (25M_J, or approximately 10,000$M_{\oplus}$); orbital periods from less than a day to many years; orbits from circular to wildly eccentric (ellipses with an "eccentricity" parameter of 0.97, corresponding to an aspect ratio of 1:4); and mean densities from 0.1 g cm^{-3} (1/10 of water) to well over 25 g cm^{-3}. Some of these planets orbit their stars in the same direction as the star spins, some orbit in the opposite direction or pass over the stellar poles. Observations have been immensely useful in constraining theories of planetary astrophysics, including with regard to the formation and evolution of planets. In this essay, I summarize some of the key results.

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Several processes have been used to discover exoplanets, but the majority have been found by one of the following four observational methods: 1) radial velocity (RV) variations of the host star; 2) brightness variations due to the transit of the planet in front of its host star(s); 3) brightness fluctuations of a background source caused by the gravitational field of the planet (called *microlensing*); and 4) direct imaging of the planet.[1]

The RV method measures the periodic change in the line-of-sight (radial) velocity of the host star, due to the gravitational pull of the planet as it revolves around the star. In other words, the star circles around the center of mass of the star-planet system because of the planet's pull, and we observe the line-of-sight component of this motion. The change in the RV of the star is measured by observing the

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Doppler shift of the stellar spectrum: the periodic blue-and-red shift of the starlight. Based on the RV signature of the star, the presence and orbital period of the planet can be established, and under certain conditions, a *minimal mass* for the planet is derived. The inclination of the orbit with respect to the line of sight remains unknown; that is, the planet may be orbiting edge-on, or almost face-on. Typical RV variations (for the star) are: approximately 200 ms^{-1} due to a Jupiter-mass object orbiting a solar-type star on a one-day period orbit, 12 ms^{-1} for the same configuration with 5.2-year period orbit (the period of Jupiter itself), and 0.09 ms^{-1} due to an Earth-mass planet orbiting a solar type star on a one-year orbit. Another key parameter measured is the "eccentricity" (ovality) of the orbit. If multiple planets orbit the same star, these parameters can be derived for all the planets.

As shown in Figure 1, the number of exoplanet detections has been rising steeply over the past decade. While, in terms of sheer numbers, the RV method was the most successful for much of the past decade, this changed in 2012, when the transit method took over (discussed later). This takeover is even more pronounced if we consider the approximately three thousand planet candidates from the *Kepler* space mission.

While the concept is simple, measuring the RV of a star at the ms^{-1} level has been a challenge, and only a few astronomical facilities have been able to achieve this. Two notable examples, among a dozen facilities, are the High Accuracy Radial velocity Planet Searcher (HARPS) on the European Southern Observatory (ESO) 3.6m diameter telescope, and the HIgh Resolution Echelle Spectrograph (HIRES) on the Keck-I 10m diameter telescope. The precision of instruments has improved significantly over a decade: for example, HARPS reaches 1 ms^{-1} precision for a moderately bright star in a one-minute exposure. For bright stars, the primary limitations on precision include instrument systematics and noise due to stellar activity. Recent record-breaking detections include a planet inducing an RV variation of only a half-meter per second on its host star (called HD 20794) and a possible Earth-mass planet around one of the brightest and closest stars, α Centauri B, causing a similar RV variation roughly equivalent to the speed of a person walking slowly.

Significant advances have been made by way of high-precision spectroscopy using "laser-combs,"[2] which provide a highly accurate and stable calibration source. High-precision *infrared* spectroscopy[3] has also been at the frontier of research, motivated by the enhanced detectability of potentially habitable Earth-mass planets around smaller (and cooler) stars. Plans for future instrumentation on the next generation of large telescopes under development are being shaped by the goal of detecting small planets. (Examples include the ESPRESSO instrument on the 8.2m diameter VLT telescope, CODEX for the future 39m E-ELT telescope, and GCLEF for the future 24m GMT telescope.)

To date, RV searches have targeted a few thousand relatively bright stars, and have discovered around five hundred exoplanets in approximately four hundred planetary systems (some of which are multi-planet systems). This sample is large enough to derive meaningful statistics, as has been done by many authors.[4] Some of the key results include: Gas giant planets with planetary mass $M_p > 50M_\oplus$ (50 Earth masses) on short-period orbits (less than ten days), also known as "hot Jupiters," are intrinsically rare, present in only around 1 percent of all star systems. However, there is an extremely strong bias favoring their discovery, which explains why the first RV detection of a Jupiter-mass planet (around the star 51 Peg) was that of a hot

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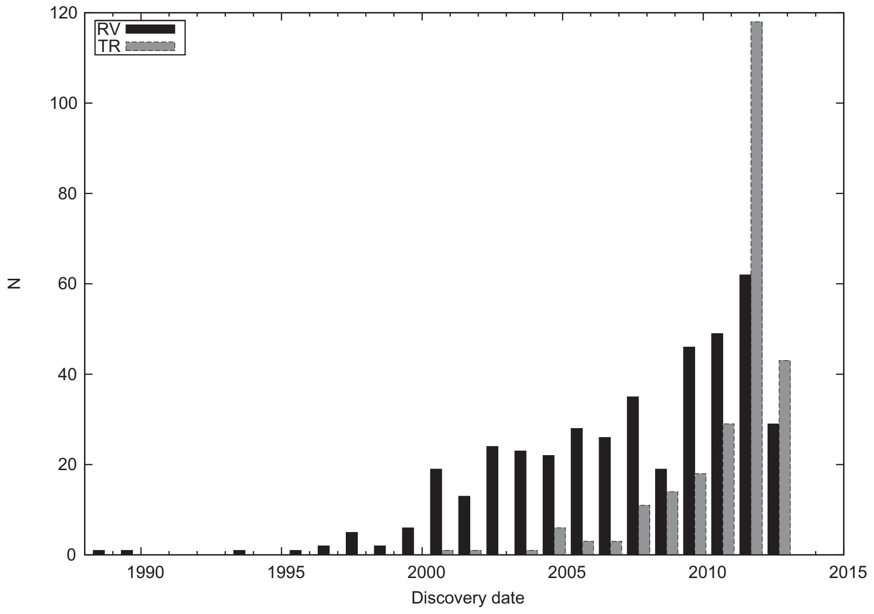
Figure 1
Number of RV (black) and Transit (gray) Detections as a Function of Year



This plot does not show planet candidates from the Kepler mission. Source: Data from exoplanets.org.

Jupiter,[5] and why most ground-based transit surveys have discovered only hot Jupiters. In contrast, "light" planets more like Earth ($M_p < 30M_\oplus$) are abundant, with a very sharp increase in the occurrence rate as planetary mass decreases. The occurrence rate of giant planets increases with the metal content (fraction of elements heavier than helium; also called "metallicity") and mass of the host star. This, however, is not true for light planets (Neptunes, super-Earths, and smaller), which have a much weaker dependence on metallicity. For giant planets, we observe a bimodal distribution in the period, with a small "pile up" at P ≈ three days (hot Jupiters) followed by a "period valley" and steep increase in the occurrence rate for P ≥ one hundred days. Light planets, however, tend to have short-period orbits, the most typical period being forty days. While giant planets exhibit a wide distribution of eccentricities (even reaching $e \approx 0.97$), small planets exhibit more circular orbits. Hot Jupiters are "lonely," with either no detectable companion or a companion on a very wide orbit. In contrast, small planets are often in multiplanetary systems[6] like our own solar system. These observational *facts* are extremely important for constraining the various planet formation and evolution theories.

Some interesting numbers on the occurrence rate of exoplanets, as based on RV searches, are as follows: three-quarters of dwarf (solar-like) stars have a planet with a period less than ten years, and one-quarter of dwarf stars have a 0.5 to $2M_\oplus$ Earth-mass planet with a period less than fifty days.[7] It may turn out, when all periods and masses are considered, that essentially all stars have planets.

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Below I list some notable exoplanetary systems that have been discovered by the RV method. Note that the nomenclature of exoplanets is such that most exoplanets carry the name of the host star together with a suffix for the planet ("b" for the first, "c" for the second, and so on). For example, the first planet discovered around the star 55 Cnc is called 55 Cnc b, the second and third planets are 55 Cnc c and 55 Cnc d, respectively.

- HD 80606 b is a massive planet on an extremely eccentric and long-period orbit, and was later found to transit its host star.
- A Neptune-mass planet orbiting a nearby M dwarf, GJ 436, was later found to transit its host star.
- Four planets were discovered around the red dwarf star Gl 876,[8] with three of them in the so-called Laplace-resonance, where the ratio of the orbital periods is 1:2:4. This configuration is strikingly similar to the inner three Galilean moons of our Jupiter.
- A system of three to six planets was found around Gl 581 (some of which are disputed), including one or more super-Earths (planets more massive than Earth, but less than about ten times the mass of Earth) close to or inside the habitable zone.
- 55 Cnc is a star visible to the naked-eye with five planets. The innermost planet (55 Cnc e) is a super-Earth on a very short-period orbit of only 0.73 days, and was later found to transit the star.
- HD 10180 has a planetary system of seven (or even more) planets, the largest number yet for exoplanetary systems!
- An Earth-mass planet was discovered, inducing only 0.5 ms^{-1} variation on α Centauri B, one of the brightest and closest stars in the sky.[9] (Note: this discovery is still debated.)

High-precision RV measurements will continue to improve in the next decade, and should reach a precision level of just a few centimeters per second. A serious limitation on the method will be stellar noise, due to either oscillations of the star or spots and other surface irregularities.

By chance alignment, our line of sight may lie in the orbital plane of an exoplanet. In this case, the planet periodically transits across the face of the star as seen from Earth. During transits, the star's light is dimmed by a fraction that is proportional to the ratio of the projected area of the planet to that of the star: that is, $(R_p/R_\star)^2$, where R_p and $R_\star$ are the planetary and stellar radii, respectively. As viewed from such a vantage point, Jupiter transiting the sun would cause a 1 percent dip in the *light curve* (the light of the star as a function of time) lasting roughly thirty hours, and Earth would cause a 0.01 percent dip for about thirteen hours.

Careful analysis of the light curve during the transit, together with RV observations of the system, yield the following parameters for the system: period, planet-to-star radius ratio, inclination (angle or orbital plane with respect to the sky plane), and semi-major axis of the planet (half of the longest diameter of the elliptical orbit, in units of the stellar radius). Further, using Kepler's third law, the following fundamental physical parameters are determined: the surface gravity of the planet and the mean density of the star. When coupled with spectroscopic observations and stellar models, the mean stellar density is, in turn, an important constraint on the mass and radius of the star. In other words, the transiting planet helps us determine the properties of its host star. Knowing the host star, then, is essential for determining the parameters of the planet.

For transiting exoplanets (TEPs), if the stellar radius is known (which is typically

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the case), the planetary radius is also determined. If RV measurements of the host star are available, and if the stellar mass is known (which is also common), then the mass of the TEP is also derived without any ambiguity (not only a lower limit, as for pure RV detections).

Astronomers recognized long ago that TEPs provide us with an unparalleled opportunity for understanding their physical properties, as one can unambiguously determine their masses, radii, mean densities, and surface gravities, among other measurements. The chance of detecting transit of a planet around a random star, however, was initially thought to be very slim, because 1) giant planets were thought to be rare; 2) the chance that we would fall in its orbital plane is tiny (for example, 1 in 1,000 for our Jupiter, as seen from a vantage point); 3) the fraction of time spent transiting is small (for example, 0.0003 for our Jupiter); and 4) the transit signature (diminution of starlight) is small (< 1 percent). Thus, it is no accident that the first TEP detection, in 2000,[10] was that of a giant planet (HD 209458 b), previously known from RV measurements to orbit a bright star on a very short-period orbit. Only a couple of years later, in 2003, the OGLE project[11] detected the first TEPs *without* prior RV measurements.[12] The enormous scientific value of transiting planets triggered a gold rush for TEPs, and a small armada of projects were undertaken. These employed primarily wide-field instruments observing tens of thousands of stars per exposure and monitoring stellar fields every clear night. Certain challenges were realized, such as the need for 1) robust automation of telescopes and data processing; 2) high-precision photometry (stellar flux measurements) over a wide field in the sky; and 3) extensive resources for following up on the planet candidates to deal with the large number of astrophysical scenarios that mimic planetary transits. Nevertheless, as TEPs became a hot topic in contemporary astrophysics, their study provided a unique opportunity for small telescopes to participate in cutting-edge science. Examples of such surveys include TrES, XO, HATNet, WASP, and HATSouth. Together, these projects have revealed approximately 150 TEPs, which are among the best characterized exoplanets. In fact, the majority (70 percent) of exoplanets with masses and radii measured to better than 10 percent accuracy were discovered by wide-field ground-based surveys.

Figure 2 plots the mass-radius diagram for around two hundred TEPs with well-determined physical parameters. Broadly speaking, the radius increases with increasing mass, but there are a number of interesting features in this figure. One is that – as theoretical physics would predict – the radii of massive planets are relatively small; that is, the planets are very dense. Also, many transiting gas giant planets on short-period orbits were found to have much larger radii than that expected for an old and cool pure hydrogen/helium body (see the top portion of Figure 2). One example is HAT-P-32 b, with mass equal to but a radius twice that of Jupiter's – meaning the planet is 1/8 Jupiter's mean density! There has been no shortage of theories to explain this "inflation" of planets. Ground-based surveys yielded a big enough sample to show that the inflation of radii (relative to those predicted) was connected to the heating by in-falling stellar flux, and perhaps by the metal content of the star. At present there is still no clear understanding of this matter.[13]

During the transit of a planet, starlight passes through the atmosphere of the planet, and a fraction of the light is absorbed, depending on the properties of the atmosphere (chemical composition, scale, height). By comparing the stellar spectrum in and out of transit, one can infer these

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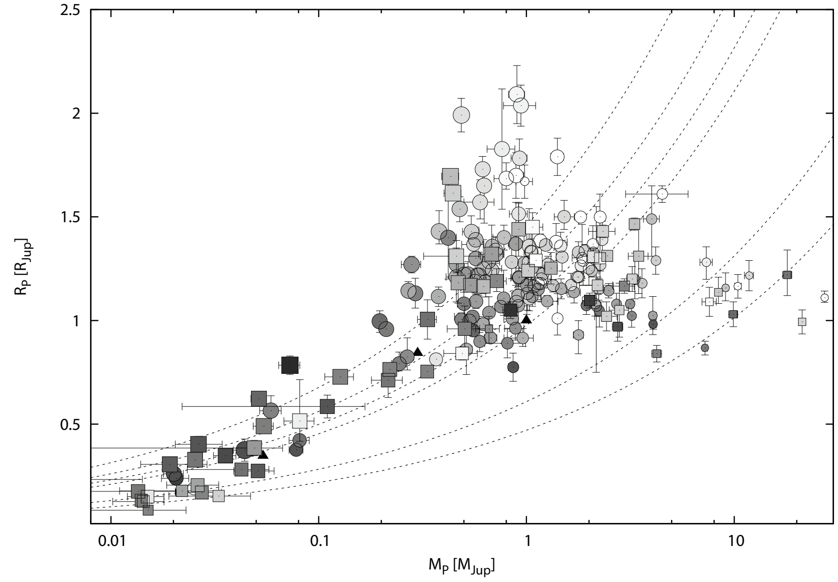
Figure 2
The Mass-Radius Diagram of Transiting Extrasolar Planets



Circles indicate ground-based discoveries, while squares show space-based discoveries. Point-size scales with the inverse of the planetary surface gravity (higher gravity = smaller points). The gray tone scales with equilibrium temperature, with the very light symbols indicating temperatures in excess of 2000 K. Dashed lines indicate iso-density lines corresponding to 0.4, 0.7, 1.0, 1.33, 5.5, and 11.9 g cm^{-3}, respectively.

properties of the planetary atmosphere. The first such measurement was the detection of sodium in the atmosphere of the planet HD 209458 b using the STIS instrument on the Hubble Space Telescope (HST). Since then, this planet has been subject to intensive studies, detecting an extended hydrogen exosphere, for example, and water absorption in the near infrared[14] via transmission spectroscopy. Another well-studied system is HD 189733 b, a gas giant on a short period orbit around a nearby star (which star is somewhat cooler than the sun). Here sodium was detected from the ground using the Hobby Eberly Telescope, and a featureless spectrum in the visible (HST/ACS) suggested haze in the atmosphere. Can you imagine the excitement if we were to detect molecular oxygen in the atmosphere of one of the planets? It would suggest that there may be life on the planet, since oxygen is very reactive and does not persist absent living organisms. (Note, however, that this is a potential "biosignature," and not definite evidence.[15])

During the occultation of a planet – that is, when the planet moves *behind* the star – the combined light from the star and planet drops (as seen from Earth). In the *infrared*, this drop is primarily due to the planet's *thermal radiation* being eclipsed by the star. By measuring the depth of the occultation, one can measure the so-called brightness temperature on the "dayside" of the planet. Such measurements have been performed for more than thirty star systems. In the case of the aforementioned HD 189733 b,[16] the "phase-curve" (total observed brightness as the planet moves

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on its orbit) was observed from before primary transit to after occultation, and night- and dayside brightness was found to reach temperatures of approximately 970 K and 1200 K, respectively. This is a relatively small difference, especially because we believe that this planet is tidally locked: the planet shows the same side to the star (just as our moon shows the same face to Earth at all times), which therefore receives an enormous radiant flux. A plausible solution is that the heat is efficiently redistributed to the nightside via circulation of winds. Even more amazing is that we now have a thermal map of this exoplanet showing that the warmest spot on the planet is 16° off (to the "east") from the point directly facing the star.

Phase-curves were automatically acquired by the *Kepler* space mission for thousands of transiting planet candidates, as it performed nonstop observations in the visible band-pass. Occultations in the *visible* light (as compared to the infrared, discussed above) are primarily due to reflected light occulted by the star, and provide a handle on the reflectivity of extrasolar planets. For the planet TrES-2 b, *Kepler*'s measurements established a stunningly low reflectivity; this planet is "pitch dark," reflecting only 2.5 percent of the infalling light.[17]

Planetary spectra were also investigated close to their occultation. By comparing the spectrum of the system during and outside occultation, one can infer the emission spectrum of the planet. Molecules such as CH_4, H_2O, and CO_2 were detected for a number of exoplanets.

Observing transmission spectra or other properties of exoplanets can be extremely challenging from the ground, due to systematic noise introduced by our own atmosphere. Nevertheless, it has been a trend in recent years to use ground-based instrumentation, such as OSIRIS on the Gran Telescopio Canarias, and multi-object spectrographs with wide slits, such as MMIRS on the Magellan Telescope. In general, astronomers made excellent use of instruments that were not originally designed to carry out such high-precision measurements, occasionally stretching beyond the capabilities of these tools. Results have sometimes been questioned by competing teams, and were shown to be very sensitive to the data analysis procedures.[18]

As hinted at earlier, another quantity that can be measured for TEPs is the angle between the orbital plane of the planet and the equator of the star, as projected onto the plane of the sky. This angle is revealed through an anomaly in the RV measurements of the star made during transit. This "Rossiter-McLaughlin" anomaly was predicted and observed for eclipsing binary stars almost a century ago, but was only applied to TEPs in the past decade.[19] Initial measurements suggested that all TEP orbits are well aligned ("prograde") with the equator of their host stars, and this almost led to a pause in the investigation of further systems. Then, highly tilted (called *high obliquity*) and even retrograde planets (circling the star in the "opposite" direction) were discovered, such as HAT-P-7 b.[20] This hot Jupiter, on a 2.2-day retrograde orbit, clearly violated the prevailing theory of giant planet formation, which argued that planets form far from the stellar heart of the system, where ices condense from the rotating protoplanetary disc and then slowly migrate inward (keeping at least the direction of their angular momentum). Astronomer Joshua Winn and colleagues concluded that hot stars with hot Jupiters have high obliquities, with the dividing line between well-aligned and misaligned systems being somewhere at stellar effective temperature higher than the sun.[21] Recently, physicist Simon Albrecht and colleagues have claimed that the star-planet obliquities for

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close-in hot Jupiters were initially random, and aligned systems are those where tidal interactions between the star and the planet are expected to be strong (see Figure 3).[22]

Space-based transit searches are qualitatively different from ground-based searches in that they have achieved much higher photometric precision than ground-based surveys, using almost uninterrupted observations to observe fainter stars. One key player was the CoRoT satellite. Perhaps one of the top scientific results of CoRoT was the discovery of CoRoT-7 b,[23] a transiting super-Earth with $1.6R_{\oplus}$ radius on a twenty-hour-period orbit, and with a mass $\leq 8M_{\oplus}$.

The other key player in exoplanet discovery is the *Kepler* space mission, which is fully dedicated to TEP detection. It was designed to have the capability of detecting an Earth-sized planet transiting a sun-like star. *Kepler* has been transformative to the field. Launched in 2009, it has been continuously monitoring a selected area in the sky, roughly the area of the Big Dipper, yielding exquisite photometry for some 150,000 stars. Most stars are observed at a thirty-minute cadence, and the per-point precision of the stellar fluxes reaches thirty parts per million! (*Kepler* failed mechanically in May 2013, and a new mission plan, "K2" or "Second Light," has been adopted to make use of *Kepler*'s remaining capabilities.) To date, *Kepler* has found some three thousand planetary *candidates*. As astrophysicist Timothy Morton and astronomer John Asher Johnson have shown, based on statistical arguments, at least 90 percent of these should be real planets, even though the classical confirmation is not available for the majority.[24]

Notably, the *Kepler* space mission found that small (radius) planets, reaching down to Earth-size, are extremely frequent. Using the *Kepler* data, Andrew Howard and colleagues found that for orbital periods shorter than fifty days, the distribution of planet radii scales with the inverse square of the planetary radius.[25] Approximately 13 percent of stars have small ($2-4R_{\oplus}$) planets with relatively short (< fifty days) periods. They also found that the occurrence of small planets in the *Kepler* field increases for cool stars (< 4000 K) by a factor of seven when compared to hot stars (> 6600 K). It also appears that while smaller planets are more frequent, this occurrence rate plateaus at about $2R_{\oplus}$; that is, planets smaller than two Earth-radii are still not more frequent. Another important finding of *Kepler* was that multiple planetary systems are intrinsically frequent: at least 27 percent of planets are in multi-transiting systems, and 15 percent of stars with TEPs host more than one planet.[26] Multiple systems consist primarily of small planets; hot Saturns and Jupiters are "lonely," with no nearby companions. A shortlist of some truly amazing planetary systems found by *Kepler* is given below.

- Kepler-11: six TEPs in a densely packed configuration, five with orbital periods between ten and forty-seven days.
- Kepler-36: a pair of planets with orbital distances differing by only 10 percent and with densities differing by a factor of eight.
- Kepler-47, the first circumbinary planetary *system*: two super-Earths orbiting at $P \approx 50$ days and $P \approx 300$ days around a pair of stars that are eclipsing each other about every seven days.
- Kepler-62: a five-planet system with planets of 1.4 and $1.6R_{\oplus}$ radii orbiting in the habitable zone (that is, they *may* host life).[27]
- KOI-872 b, c: the detection and characterization of a nontransiting planet (KOI-872 c) by variations (due to gravitational interaction) induced on the transit times of the transiting planet (KOI-872 b).

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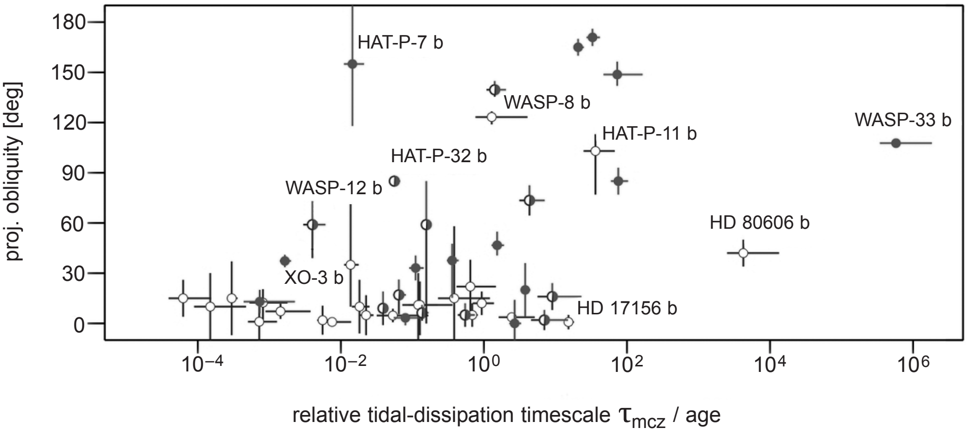
Figure 3
Obliquity of Transiting Exoplanets with Respect to the Spin Axis of Their Host Stars



The vertical axis shows the obliquity of the planets with respect to the stellar spin axis, projected on the sky plane. Zero degrees means a perfectly aligned prograde orbit, and 180 degrees means retrograde orbit. The horizontal axis shows the estimated timescale required for aligning a planet with the stellar spin axis. Stars with temperatures higher than 6250 K are shown with filled symbols. Open symbols show stars with temperatures lower than 6250 K. Source: Simon Albrecht et al., "Obliquities of Hot Jupiter Host Stars: Evidence for Tidal Interactions and Primordial Misalignments," *The Astrophysical Journal* 757 (2012): 18, arXiv:1206.6105; used here with permission of the American Astronomical Society.

- KOI-142: similar case to KOI-872, but also using variations in the transit duration (for the first time) to determine the system parameters.

The next decade will be extremely promising in terms of scientific progress based on transiting planets. The U.S.-based TESS mission, with a proposed launch sometime in 2017, will scan the entire sky to detect thousands of transiting planets around the brightest stars near Earth. Among these will be potentially habitable super-Earths amenable to follow-up observations. The James Webb Space Telescope (JWST) and the European EChO space mission will observe atmospheres of TEPs through transmission and occultation spectroscopy at unprecedented precision. There is hope that by the next decade we will actually detect bio-signatures in the atmospheres of remote worlds.

The past decade saw real breakthroughs in the direct imaging of exoplanets. The task is extremely challenging because stars are bright while planets are faint and appear close to the stars; thus, capturing and separating the light emanating from the planet requires very-high-contrast and high-spatial-resolution imaging. For these reasons, state-of-the-art instrumentation has been developed and used on the largest telescopes, employing infrared imaging, adaptive optics, coronography, and novel observing and data analysis techniques. The targets typically are young (a few million years old) stars, because these may have young planetary systems, in which the planets still emit excess (infrared) light due to their primordial heat.

One spectacular success was direct imaging of the planets around the young star HR 8799.[28] Not only were the planets clearly visible, but their face-on orbital motion

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around the star was also apparent on images taken a year apart. Another important discovery was the planet orbiting the very bright and nearby star, β Pictoris.[29] This star has a disk of debris (dust and rocks) that is almost edge-on. An approximately $8M_J$ planet around the same star was detected on archival images from 2003, then reobserved in 2009 on the other side of the star! Finally, a very recent detection is the $13M_J$ mass single gas giant around the star "κ And," detected with the Subaru/HiCIAO instrument as part of the SEEDS survey.[30]

Another breakthrough was the ability to take *spectra* of the directly imaged planets. This was done for all four planets around HR 8799 by Project 1640 on the venerable Palomar 5m telescope.[31] The low-resolution spectra show an unexpected diversity among the four planets, with hints of CH_4, NH_3, CO_2, and other molecules. Massive current efforts (NICI, SEEDS) and future projects (GPI, SPHERE) will certainly yield many more directly imaged planets with spectra.

An object (star or planet), by virtue of its finite mass, will perturb the light from a background source that falls along the line of sight, creating multiple images and magnifying the source. As the object ("lens") moves with respect to the background source, the magnification changes in time, resulting in the brightening of the background source. The brightening, as the function of time (the light curve), has a characteristic "bell-shape." This effect, predicted by Einstein, has now become a practical astronomical tool. Thousands of such microlensing events[32] are now detected every year by surveys such as OGLE[33] and MOA.[34] Planets around the lensing star cause further perturbation of the light, and appear as anomalies on the microlensing light curve. To date, some thirty or so planets have been discovered via microlensing. An interesting aspect of microlensing is its sensitivity toward low-mass planets on wide orbits, even free-floating planets without a host star. Microlensing is sensitive to classes of planets that currently cannot be found by RV, transit, or direct-imaging searches.

The first microlensing-detected planet was a 2.6 Jupiter-mass object at a 5 AU orbit (astronomical unit, the mean distance between the Earth and the sun: 149.6 million kilometers).[35] Microlensing detected planets more massive than Jupiter around very small stars,[36] which is somewhat surprising given the scarcity of such objects found by RV and transit searches. It is also from microlensing that we learned about the existence of cold super-Earths that orbit their stars beyond the ice-line (distance beyond which it is cold enough for ices to form) at several AU distance. Multiple planetary systems, such as a Jupiter/Saturn analogue, were also detected by microlensing.[37] Recently, microlensing has found signals due to free-floating planets, and has concluded that such planets are twice as common in our galaxy as main-sequence stars.[38]

While progress in the field of exoplanets over the past decade has been spectacular, most of the excitement is yet to come. This includes finding analogues of our solar system, planets similar to our Earth, and moons around exoplanets. We hope to detect biomarkers and – ultimately – signs of intelligent life capable of communication with us, however slow the turnaround time may be.

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ENDNOTES

Author's Note: I thank Joel Hartman and Jeremiah Ostriker for careful reading of this manuscript. I apologize to those whose work I could not discuss due to space limitations.

1 Michael Perryman, *The Exoplanet Handbook* (Cambridge: Cambridge University Press, 2011).

2 Gaspare Lo Curto et al., "Achieving a Few cm/sec Calibration Repeatability for High Resolution Spectrographs: The Laser Frequency Comb on HARPS," *Proceedings of SPIE* (2012): 8446.

3 Peter Plavchan et al., "Precision Near-Infrared Radial Velocity Instrumentation and Exoplanet Survey," American Astronomical Society, AAS Meeting No. 221, #109.06, 2013.

4 For example, Andrew W. Howard et al., "The Occurrence and Mass Distribution of Close-in Super-Earths, Neptunes, and Jupiters," *Science* (330) (2010): 653.

5 Michel Mayor and Didier Queloz, "A Jupiter-Mass Companion to a Solar-Type Star," *Nature* (378) (1995): 355.

6 Michel Mayor et al., "The HARPS Search for Southern Extra-Solar Planets XXXIV: Occurrence, Mass Distribution and Orbital Properties of Super-Earths and Neptune-Mass Planets," *Astronomy & Astrophysics* (2011), arXiv:1109.2497.

7 Andrew W. Howard et al., "Planet Occurrence within 0.25 AU of Solar-Type Stars from Kepler," *The Astrophysical Journal Supplement* (201) (2012): 15.

8 Eugenio Rivera et al., "The Lick-Carnegie Exoplanet Survey: A Uranus-Mass Fourth Planet for GJ 876 in an Extrasolar Laplace Configuration," *The Astrophysical Journal* (719) (2010): 890.

9 Xavier Dumusque et al., "An Earth-Mass Planet Orbiting α Centauri B," *Nature* (491) (2012): 207.

10 David Charbonneau et al., "Detection of Planetary Transits Across a Sun-Like Star," *The Astrophysical Journal* (529) (2000): L45.

11 Andrzej Udalski et al., "The Optical Gravitational Lensing Experiment: Search for Planetary and Low-Luminosity Object Transits in the Galactic Disk. Results of 2001 Campaign," *Acta Astronautica* (52) (2002): 1.

12 M. Konacki et al., "An Extrasolar Planet that Transits the Disk of Its Parent Star," *Nature* (421) (2003): 507.

13 For a review, see David S. Spiegel and Adam Burrows, "Thermal Processes Governing Hot-Jupiter Radii," *The Astrophysical Journal* (2013), arXiv:1303.0293.

14 D. Deming et al., "Infrared Transmission Spectroscopy of the Exoplanets HD 209458 b and XO-1 b Using the Wide Field Camera-3 on the Hubble Space Telescope," *The Astrophysical Journal* (774) (2013): 95, arXiv:1302.1141.

15 Hanno Rein, Yuka Fujii, and David S. Spiegel, "Some Inconvenient Truths about Biosignatures Involving Two Chemical Species on Earth-Like Exoplanets," *Proceedings of the National Academy of Sciences* 111 (19) (2014): 6871–6875.

16 Heather A. Knutson et al., "A Map of the Day-Night Contrast of the Extrasolar Planet HD 189733 b," *Nature* (447) (2007): 183.

17 David M. Kipping and David S. Spiegel, "Detection of Visible Light from the Darkest World," *Monthly Notices of the Royal Astronomical Society* (417) (2011): L88.

18 For example, see Deming et al., "Infrared Transmission Spectroscopy of the Exoplanets HD 209458 b and XO-1 b Using the Wide Field Camera-3 on the Hubble Space Telescope."

19 D. Queloz et al., "Detection of a Spectroscopic Transit by the Planet Orbiting the Star HD 209458," *Astronomy and Astrophysics* (359) (2000): L13; and Joshua N. Winn et al., "Measurement of Spin-Orbit Alignment in an Extrasolar Planetary System," *The Astrophysical Journal* (631) (2005): 1215.

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[20] Joshua N. Winn et al., "HAT-P-7: A Retrograde or Polar Orbit, and a Third Body," *The Astrophysical Journal* (703) (2009): L99.

[21] Joshua N. Winn et al., "Hot Stars with Hot Jupiters Have High Obliquities," *The Astrophysical Journal* (718) (2010): L145.

[22] Simon Albrecht et al., "Obliquities of Hot Jupiter Host Stars: Evidence for Tidal Interactions and Primordial Misalignments," *The Astrophysical Journal* 757 (2012): 18, arXiv:1206.6105.

[23] D. Queloz et al., "The CoRoT-7 Planetary System: Two Orbiting Super-Earths," *Astronomy and Astrophysics* (506) (2009): 303.

[24] Timothy D. Morton and John Asher Johnson, "On the Low False Positive Probabilities of *Kepler* Planet Candidates," *The Astrophysical Journal* (738) (2011): 170.

[25] Howard et al., "Planet Occurrence within 0.25 AU of Solar-Type Stars from *Kepler*."

[26] Ibid.

[27] William J. Borucki et al., "Kepler-62: A Five-Planet System with Planets of 1.4 and 1.6 Earth Radii in the Habitable Zone," *Science* (340) (2013): 587, arXiv:1304.7387.

[28] Christian Marois et al., "Direct Imaging of Multiple Planets Orbiting the Star HR 8799," *Science* (322) (2008): 1348; and Christian Marois et al., "Images of a Fourth Planet Orbiting HR 8799," *Nature* (468) (2010): 1080.

[29] A.-M. Lagrange et al., "A Probable Giant Planet Imaged in the Beta Pictoris Disk: VLT/NaCo Deep L'-band Imaging," *Astronomy & Astrophysics* (493) (2009): L21.

[30] J. Carson et al., "Direct Imaging Discovery of a 'Super-Jupiter' around the Late B-Type Star κ," *The Astrophysical Journal* (763) (2013): L32.

[31] B. R. Oppenheimer et al., "Reconnaissance of the HR 8799 Exosolar System. I. Near-Infrared Spectroscopy," *The Astrophysical Journal* (768) (2013): 24.

[32] B. Paczyński, "Gravitational Microlensing by the Galactic Halo," *The Astrophysical Journal* (304) (1986): 1.

[33] Andrzej Udalski, " The Optical Gravitational Lensing Experiment. Real Time Data Analysis Systems in the OGLE-III Survey," *Acta Astronautica* (53) (2003): 291.

[34] T. Sako et al., "MOA-cam3: A Wide-Field Mosaic CCD Camera for a Gravitational Microlensing Survey in New Zealand," *Experimental Astronomy* (22) (2008): 51.

[35] I. A. Bond et al., "OGLE 2003-BLG-235/MOA 2003-BLG-53: A Planetary Microlensing Event," *The Astrophysical Journal* (606) (2004): L155 – L158.

[36] Andrzej Udalski et al., "A Jovian-Mass Planet in Microlensing Event OGLE-2005-BLG-071," *The Astrophysical Journal* (628) (2005): L109.

[37] B. S. Gaudi et al., "Discovery of a Jupiter/Saturn Analog with Gravitational Microlensing," *Science* (319) (2008): 927.

[38] T. Sumi et al., "Unbound or Distant Planetary Mass Population Detected by Gravitational Microlensing," *Nature* (473) (2011): 349.

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