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Introductory review on transiting planets

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The ground based searches for transiting planets - an overview
Transiting planets with HATNet

Speaker: Gaspar Bakos
Co-authors: Geza Kovacs, Robert Noyes, Guillermo Torres, David Latham, Dimitar Sasselov, Brigitta Sipocz, Andras Pal, Gabor Kovacs, Jose Fernandez, Gil Esquerdo

The HATNet project at the CfA has contributed quite significantly to the transiting planet inventory through finding seven (or more) planets. I will give background information on HATNet, describe how we search for planets, and comment on some of our more interesting detections.

The WASP transit surveys

The WASP consortium operates two wide-field camera arrays in the northern (La Palma) and southern (Sutherland) hemispheres. Each installation comprises a robotic mount bearing 8 cameras, forming a mosaic with a field of view of 30 degrees in declination by 1 hour in RA. I shall describe the system performance, observing strategy, candidate selection procedures and follow-up campaigns, and the yield and physical characteristics of the 15 (or more) planets discovered in the course of the survey to date.
The MEarth project: searching for transiting habitable super-Earths around nearby M-dwarfs

Due to their small radii, M-dwarfs are very promising targets to search for transiting super-Earths, with a planet of 2 Earth radii orbiting an M5 dwarf in the habitable zone giving rise to a 0.5% photometric signal, with a period of two weeks. This can be detected from the ground using modest-aperture telescopes by targeting samples of nearby M-dwarfs. Such planets would be very amenable to follow-up studies due to the brightness of the parent stars, and the favourable planet-star flux ratio. MEarth is such a transit survey of ~2000 nearby M-dwarfs. Since the targets are distributed over the entire (Northern) sky, it is necessary to observe them individually, which will be done by using 8 independent 0.4m robotic telescopes, two of which have been in operation since December 2007 at Mount Hopkins, Arizona. We discuss the survey design and hardware, and report on the current status of the survey, and preliminary results obtained from the commissioning data.

Transiting Planets in the Galactic Bulge and Implications

The exoplanets discovered so far have been mostly around relatively nearby and bright stars. As a result, the host stars are mostly (i) in the Galactic disk, (ii) relatively massive, and (iii) relatively metal rich. The SWEEPS project was aimed at extending our knowledge to stars which (i) are in a different part of the Galaxy, (ii) have low masses, and (iii) have a large range of metallicities. We used the Hubble Space Telescope to monitor 180,000 F, G, K, and M dwarfs in the Galactic bulge continuously for 7 days in order to look for transiting planets. We discovered 16 candidate transiting extrasolar planets with periods of 0.6 to 4.2 days, including a new class of ultra-short period planets (USPPs) with P < 1 day. Radial velocity observations of two brightest host stars support the planetary nature of the transiting companions. These results suggest that the planet frequency in the Galactic bulge is similar to that in the solar neighborhood. They also suggest that higher metallicity favors plant formation even in the Galactic bulge. The USPPs occur only around low-mass stars which may suggest that close-in planets around higher-mass stars are irradiately evaporated, or that planets are able to migrate to and survive in close-in orbits only around such old and low-mass stars.
Transits against Fainter Stars: The Power of Image Deconvolution

Compared to bright star searches, surveys for transiting planets against fainter (V=12-18) stars have the advantage of much higher sky densities of target primaries --- a considerably larger proportion of which are dwarf stars. Furthermore, deep searches are capable of probing a wider range of stellar environments. On the other hand, for a given spatial resolution, deep searches are more prone to confusion from blended eclipsing binaries. We present a powerful mitigation strategy for the blending problem that includes the use of image deconvolution and high resolution imaging. The techniques are illustrated with Lupus-TR-3 and very recent IR imaging with PANIC on Magellan.

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Varibility characterization of stellar fields with BEST and BEST II

BEST and BEST II are two small-aperture telescopes designed to operate as a ground based support for the CoRoT space mission. Both systems are dedicated to perform precise photometric variability characterization of selected stellar fields. For both telescopes the large field of view provides the possibility of monitoring several thousands of stars over long periods of time and with high photometric precision thereby allowing the detection of faint variable stars and transiting Jupiter-sized extrasolar planets. BEST is a remotely controlled 19.5 cm aperture Schmidt-Cassegrain telescope with a 3x3 deg field of view located at Observatoire de Haute Provence, France. BEST II consists of a 25 cm aperture Baker-Ritchy-Chretien telescope with a 1.7x1.7 deg field of view. The telescope is located at Observatorio Cerro Armazones, Chile and is operated in robotic mode. We will report on the present status and most recent scientific results of both telescope systems.
Predicting the Yields of Photometric Surveys for Transiting Extrasolar Planets

We develop a method for predicting the yield of transiting planets from a photometric survey given the parameters of the survey (nights observed, bandpass, exposure time, telescope aperture, locations of the target fields, observational conditions, and detector characteristics), as well as the underlying planet properties (frequency, period and radius distributions). Using our updated understanding of transit surveys provided by the experiences of the survey teams, we account for those factors that have proven to have the greatest effect on the survey yields. Specifically, we include the effects of the surveys window functions, adopt revised estimates of the giant planet frequency, account for the number and distribution of main-sequence stars in the survey fields, and include the effects of Galactic structure and interstellar extinction. We approximate the detectability of a planetary transit using a signal-to-noise ratio (S/N) formulation. We argue that our choice of detection criterion is the most uncertain input to our predictions, and has the largest effect on the resulting planet yield. Thus drawing robust inferences about the frequency of planets from transit surveys will require that the survey teams impose and report objective, systematic, and quantifiable detection criteria. Nevertheless, with reasonable choices for the minimum S/N, we calculate yields that are generally lower, more accurate, and more realistic than previous predictions. As examples, we apply our method to the Trans-Atlantic Exoplanet Survey, the XO survey, and the Kepler mission. We discuss red noise and its possible effects on planetary detections. We conclude with estimates of the expected detection rates for future wide-angle synoptic surveys.
CoRoT-exo-1b: The first planet discovered from space

The pioneer space mission for photometric planet searches, CoRoT, steadily monitors about 12000 stars in each of its fields of view it is able to detect transit candidates early in the processing of the data and before the end of a run of observation. We report the detection of the first planet discovered by CoRoT and characterizing it by follow-up observations.

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A quest for the secondary eclipse of CoRoT-Exo-2b, and a study of its transit timing variations

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The second transiting exoplanet discovered by the CoRoT mission orbits an active K star. This causes a modulation of the stellar flux in a ~4.5 d scale, due to stellar rotation and evolving active regions on the star, what makes the secondary eclipse detection a challenging task. Star spots are also detected when the planet transits its host star, and they can induce spurious detections of transit timing variations. We will present a study devoted to the search for these two signatures on the ~150d almost continuous observations (duty cycle 93%) by the CoRoT satellite.
Properties of starspots on CoRoT-Exo-2

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As a planet eclipses its parent star, a dark starspot may be occulted, causing a detectable variation in the light curve. A total of 77 consecutive transit light curves of CoRoT-Exo-2b were observed, corresponding to an interrupted period of 134 days, since the orbital period is 1.743 days. By analyzing small deviations in the transit light curves of CoRoT-Exo-2b, it was possible to detect about 20 starspots. These were fit by a model which simulates the spots physical properties such as size, intensity, position, and temperature. The average size of these spots, or spot groups, was about half the planet size, or 0.7 R_Jup. The intensity varied from 0.1 to 0.7 of the disk center intensity, which can be converted to temperature by assuming blackbody emission for both the photosphere and the spots. Considering an effective temperature of 5625 K for the star, the spots temperature range from 3700 to 5200 K, which are 400-2000 K cooler than the rest of the disk. Moreover, by considering the star rotation period of 4.54 days, it was possible to follow the same spot on a later transit and thus infer its temporal evolution in size and intensity. The spots on CoRoT-Exo-2 were seen to rise and decay in intensity, lasting for about 50 to 100 days, which is longer than the sunspot lifetime.

The yield of transit surveys: global analysis application to CoRoT

F. Fressin, T. Guillot, F. Pont, L. Nesta

We present here the results of our statistical simulator CoRoTlux of transit surveys. We directly simulate a population of stars corresponding to the analyzed transit surveys and assign them planetary companions based on extrasolar planets discovered by radial velocimetry. We use a model of the evolution and structure of giant planets that assumes a variable fraction of heavy elements. We then apply a detection criterion considering the observation window and white and red noise levels. This simulation is both used to predict and to interpret the yield of transit surveys, by comparing the output list of detectable planets of the simulations to the real detections. We first simulated the yield of OGLE survey. Being able to reproduce qualitatively and quantitatively the yield of OGLE, this study confirmed that the two data sets from Radial Velocity and transits were compatible provided a fraction of very short period planets is added to the Radial Velocity sample. We have also shown that evolution models fitting present observational constraints predict a lack of small giant planets with large masses. We then studied if the observed potential groups (e.g. two classes linked to their Safronov number) or correlations (Mass vs. period, Surface gravity vs. period, Radius vs. Stellar Teff) within transiting giant planets characteristics had statistical significance. We are using statistical tools (e.g. LOGIT multi-parameter analysis from Econometry) to test if our results match the distribution of the known characteristics of transiting planets and their parent stars. We apply CoRoTlux to simulate CoRoT satellite yield and understand the limits of its photometry. We are using two different approaches: the first one is doing usual CoRoTlux simulations, but with the noise regime observed in ligt curves and effective detection criteria. The second approach is to generate transit events with CoRoTlux, inject them into empty CoRoT lightcurves and blindly test which are (un)detected and why. This study is useful to understand and improve CoRoT photometry, and it will help constraining the frequency and characteristics of close-in smaller planets.
Measuring accurate transit parameters

Transits are wonderfully illuminating events, bearing information about both the planet and the star that shed light on planetary structure and formation. I will review analytic work on the information content of transit photometry and spectroscopy (the Rossiter-McLaughlin effect), survey the existing highest-precision data, and present some of the theoretical inferences that can already be drawn. I will also discuss future prospects for achieving greater precision and observing higher-order effects.

Characterizing the Eccentricities of Transiting Extrasolar Planets with Kepler and CoRoT

Radial velocity planet searches have revealed that many giant planets have large eccentricities, in striking contrast with the giant planets in the solar system and prior theories of planet formation. The realization that many giant planets have large eccentricities raises a fundamental question: Do terrestrial-size planets of other stars typically have significantly eccentric orbits or nearly circular orbits like the Earth? While space-based missions such as CoRoT and Kepler will be capable of detecting nearly Earth-sized planets, it will be extremely challenging to measure their eccentricities using the with radial velocity observations. We describe how measurements of transit durations can be used to characterize the distribution of orbital eccentricities for various populations of transiting planets (e.g., nearly Earth-sized planets in the habitable zone) based on photometric observations (and estimates of the host star properties) without relying on radial velocity observations. We show that applying this technique to terrestrial planets found by Kepler can place constraints on theories for the excitation of eccentricities and tidal dissipation.
Pushing the precision limit of ground-based transit photometry

It is generally considered that ground-based photometry cannot reach the high cadence sub-mmag regime because of the presence of the atmosphere. Indeed, high frequency atmospheric noises (mainly scintillation) limit the precision that high SNR photometry can reach within small time bins. If one is ready to damage the sampling of his photometric time-series, binning the data (or using longer exposures) allows to get better errors, but the obtained precision will be finally limited by low frequency noises. To observe several times the same planetary transit and to fold the photometry with the orbital period is thus generally considered as the only option to get very well sampled and precise transit light curve from the ground. Nevertheless, we show here that reaching the sub-mmag sub-min regime for one transit is possible with a ground-based instrument. We discuss the limits of ground-based photometry and its potential for transiting planets characterization, secondary eclipses measurement and small planets detection.

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Radial velocity follow-up observations

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Recent results for follow-up observations of transiting planet with the Euler Swiss telescope.

The Euler Swiss telescope is intensively used for follow-up observations on transiting candidates found by the SuperWasp program and the Corot satellite. Observations are carried out with both the Coralie spectrograph, recently upgraded, and the EulerCam imager. To optimize the efficiency of this follow-up works, new strategies including a combination of radial velocity techniques and photometry have been developed. Euler observations have led to the recent successful announcements of many new planets as part of our collaboration with the SuperWasp program and the Corot mission.

The Rossiter-McLaughlin Effect and a Possible Spin-Orbit Misalignment in HD17156b

HD17156b is a transiting planet with high orbital eccentricity discovered in 2007 (Fischer et al. 2007, Barbieri et al. 2007). We conducted simultaneous photometric and spectroscopic observations around its transit phase to monitor the Rossiter-McLaughlin effect in this system. By modeling the Rossiter-McLaughlin effect, we found the angle between the sky projections of the orbital axis and the stellar rotation axis to be $62^{\pm25}$ deg (Narita et al. 2008). Such a large spin-orbit misalignment, as well as the large eccentricity, is consistent with the predictions by recent planetary migration models considering planet-planet scattering during the planet formation epoch (e.g., Chatterjee et al. 2007, Nagasawa et al. 2008). We report the results of our observations and future prospects for similar measurements of spin-orbit alignments in transiting planetary systems.
The precision radial velocity (RV) technique for single stars is the driving force in the extrasolar planets field. It has been used to detect most of the known extrasolar planets as well as confirm and characterize transiting planet candidates from photometric surveys. Binary (and multiple) stars were traditionally omitted from the surveys due to problems with obtaining high RV precision for their components. In particular, the original iodine absorption cell approach was not designed to measure RVs of binary stars. Yet, more than a half of the stars from the solar neighbourhood are in binary or multiple star systems. It is thus tempting to find a way to precisely measure RVs of binary stars not only for the extrasolar planets but also general stellar astronomy purposes. To this end, I have developed a novel modification of the iodine cell technique which can handle spectra of spectroscopic binary stars. In 2003, I have initiated an RV survey for planets in/around binary and multiple star systems with the Keck I/HIRES and two years later presented an approach that can routinely deliver RV precision of 20-30 m/s for binary stars. Over the last two years I have modified this approach by introducing changes to the numerical side of the method and substantially modifying the method itself. Now, the method can in favourable cases produce RV precision as high as 5 m/s for the components of double-lined spectroscopic binary stars (SB2s). Moreover, my data set of spectra of ~10 SB2s from the Keck I/HIRES and the TNG/SARG spanning four years indicates that if a binary star satisfies typical requirements - a sufficiently late spectral type, low vsin(i), low level of activity - then a near-photon limited RV precision can be obtained. Hence, this approach allows one to search for planets in/around binary stars through RV measurements and also to carry out a spectroscopic follow-up of transiting planet candidates in binary stars if needed. For example, the existing extensive databases of light curves from the ground-based efforts and soon space-based ones should enable us to verify whether there exist transiting circumbinary planets around eclipsing binary stars. Such candidate planets can now be followed spectroscopically. I will discuss my method, the ongoing effort to detect circumbinary planets through RVs and prospects for spectroscopic follow-up of transiting circumbinary planet candidates.

The Keck eta_Earth project

The Keck eta_Earth project seeks to detect and characterize a statistically significant sample of planets with masses between 3 and ~20 Earth masses. With 1 m/s radial-velocity precision, these measurements will provide one the first estimates of the fraction of stars with Earth-like planets. In all likelihood, some of these planets (with masses comparable to GJ436b, or smaller) will transit, offering rich opportunities for transit and secondary eclipse observations (of nearby, bright targets) to measure densities and constrain atmospheric/physical models of low-mass planets. This survey focuses on the nearest 250 GKM main sequence stars, all older than 2 Gyr (and hence chromospherically quiet), and accessible from Keck. Most of these stars have velocity rms under 2 m/s and are likely impoverished in detectable rocky planets within 0.1 AU. The remaining ~50 stars -- which are certainly enriched in rocky planets compared to the original 250 stars -- are observed on several ongoing high-cadence runs (7-10 consecutive nights) to identify the true planets and tease out their orbital characteristics. My presentation will focus on the transit-related aspects of this search, recent discoveries of super-Earths, and some initial constraints on the population of these objects.
Towards the characterization of the Hot-Neptune/Super-Earth population around nearby bright stars

Preliminary results from the HARPS high-precision radial velocity planet search show the existence of an important population of close-in ice giants and super-Earths around nearby solar-type stars. We expect that the number of candidates revealed by HARPS will soon be sufficient to comprise at least one transiting object. However, only space-based observations will be able to detect this transit. Given the impressive amount of information that can be obtained with HST/Spitzer on planets transiting bright stars, we would like to emphasize the scientific potential of a systematic search for transits among suitable HARPS candidates with HST/Spitzer. This would be a relatively inexpensive way to characterize for the first time a nearby super-Earth, and this on a rather short timescale.

A 5 Mearth Super-Earth Orbiting GJ 436

Most of the presently identified exoplanets have masses similar to that of Jupiter and therefore are assumed to be gaseous objects. With the ever-increasing interest in discovering lower-mass planets, several of the so-called super-Earths (1 Mearth-10 Mearth), which are predicted to be rocky, have already been found. Here we report the possible discovery of a planet around the M-type star GJ 436 with a minimum mass of 4.7+/-0.6 Mearth and a true mass of ~5 Mearth, which would make it the least massive planet around a main-sequence star found to date. The planet is identified from its perturbations on an inner Neptune-mass transiting planet (GJ 436b), by pumping eccentricity and producing variations in the orbital inclination. Analysis of published radial velocity measurements indeed reveals a significant signal corresponding to an orbital period that is very close to the 2:1 mean motion resonance with the inner planet. The near-grazing nature of the transit makes it extremely sensitive to small changes in the inclination.
The puzzling eccentricity of GJ 436b : a case of multi-techniques follow-up observations.


Among the peculiarities of GJ 436b, its high eccentricity (\(e \sim 0.14\)) is remarkable for such a short-period planet (\(P \sim 2.6\) day). Already suspected in the radial-velocity data (Butler et al. 2004 Maness et al. 2007), GJ 436b's high eccentricity found an independent -- and dramatic -- confirmation by the timing difference between primary and secondary eclipses (\(e=0.14 \pm 0.01\) -- Demory et al. 2007 Deming et al. 2007). Given an estimated age 2 Gyr, GJ 436b is expected to have dissipated its orbital eccentricity through tidal interaction with its host star. Its present orbital state is therefore puzzling. One offered explanation is the possible presence of an additional planet in the system. We propose to present our search for this putative companion, using radial-velocity measurements, transit timings and high contrast imaging.

The HARPS/Laser-Comb spectrometer: Understanding super-Earth geochemistry

The novel spectrometer design combining HARPS technology with a femtosecond laser astro-comb is a dramatic improvement in Doppler shift precision. However planet mass determination will remain the limiting factor in deriving mean densities of super-Earths. We discuss what aspects of super-Earth geochemistry can be studied with such observational constraints, based on our most current theoretical geophysical models.
Precision Radial Velocities in the Near Infrared with TEDI

The TEDI (TripleSpec - Exoplanet Discovery Instrument) is a dedicated instrument for near infrared radial velocity searches for planetary companions to low-mass stars with the goal of achieving meters per second radial velocity precision. Heretofore, such planet searches have been limited almost entirely to the optical band and to stars that are bright in this band. Consequently, knowledge about planetary companions to the populous but visibly-faint low mass stars is limited. In addition to the opportunity afforded by precision radial velocity searches directly for planets around low mass stars, transits around the smallest M dwarfs offer a chance to detect the smallest possible planets in the habitable zones of the parent stars. As has been the case with followup of planet candidates detected by the transit method requiring radial velocity confirmation, the capability to undertake efficient precision radial velocity measurements of mid-late M dwarfs will be required. TEDI has been commissioned on the Palomar 200 telescope in December 2007, and is currently in a science verification phase. A description of the instrument and a discussion of current performance will be presented.
Observations of bright transiting exoplanets with the MOST satellite.
I will present an update on observations of the transiting exoplanetary system HD 209458 and HD 189733 with the MOST (Microvariability and Oscillations of STars) satellite. Topics will include long term variability of the host stars, current limits on the optical reflectivity of the planets and the prospects of future observations.

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Interior and structure of giant planets

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Talk # 30 5/21/2008 9:00 AM
Probing the Interiors of Very Hot Jupiters Through Transit Timing

Of the dozens of transiting extrasolar planets with known masses, quite a few are seen to have radius anomalies, being either larger or smaller than simple structure theory would predict. The undersized objects have been interpreted to have dense cores of heavy elements, while the oversized objects are said to have large puffed up outer envelopes. In an attempt to explain the radii anomalies, it is necessary to appeal to some missing physics in the modeling process, either in changes to the opacities, equations of state, or an additional heat sources (Guillot, 2007). While the solution to this problem is currently unknown, the anomalies clearly depend on the diversity of planetary interiors. We show that the currently unknown interior properties of extra-solar planets can be directly measured by observing the apsidal precession due to the tidal and rotational bulges, as evidenced by subtle but observable changes in the transit light curves (Ragozzine Wolf, 2008, ApJ, pending submission). Other authors have suggested using transit timing to observe the effects of general relativity, stellar oblateness, or additional planets in the system. We show that precession due to the quadrupole moment of the planet dominates over other perturbations by 1-2 orders of magnitude in the case of single very hot Jupiters (a ~ 0.02 AU). We assess the realistic measurement accuracy of extra-solar gravitational moments (e.g. J2) by generating and fitting synthetic photometry observations and find that it is a sensitive function of eccentricity, but clearly measurable for reasonable eccentricities (~3e-3  e  0.1). We will discuss the capabilities of this new technique to directly characterize the diversity of extra-solar planet interiors in light of future observations, particularly those provided by the Kepler space-based photometry mission (Wolf Ragozzine, 2008, ApJ, in preparation).
Effects of oxidation on building rocky planets: from Mercury to a coreless terrestrial exoplanet

Differentiation in terrestrial planets is expected to include the formation of a metallic iron core. We predict the existence of terrestrial planets that have differentiated but have no metallic coreplanets that are effectively a giant silicate mantle. We discuss two paths to forming a coreless terrestrial planet, whereby the oxidation state during planetary accretion and solidification will determine the size or existence of any metallic core. Under this hypothesis, any metallic iron in the bulk accreting material is oxidized by water, binding the iron in the form of iron oxide into the silicate minerals of the planetary mantle. The existence of such silicate planets has consequences for interpreting the compositions and interior density structures of exoplanets based on their mass and radius measurements.

The Range of atmospheric mass and composition for super Earths

Terrestrial planets may obtain atmospheres from three primary sources: capture of nebular gases, degassing during accretion, and degassing from subsequent tectonic activity. Here we model degassing during accretion for super Earths, using bulk compositions drawn from primitive and differentiated meteorite compositions. Theory of planetary accretion allows for reducing or oxidizing conditions, and for additions of water-rich material from greater radius in the planetary disk, producing a range of atmosphere-forming conditions. Hydrogen can be released as a result of oxidizing metallic iron with water, and excess water and carbon can produce atmospheres through simple degassing. We show that degassing alone can create significant planetary atmospheres, reaching up to ~6% by planet mass of hydrogen, ~20% by mass of water, and ~5% by mass of carbon compounds. Modest initial water contents (10% or more by mass) can create planets with deep surface liquid water oceans soon after accretion is complete. Photochemistry and atmospheric escape will determine the final atmospheric mass and composition.
What to Expect from Transiting Multiplanet Systems

So far radial velocity (RV) measurements have discovered ~25 stars to host multiple planets. The statistics imply that many of the known hosts of transiting planets should have additional planets, yet none have been solidly detected. They will be soon, via complementary search methods of RV, transit-time variations (TTV) of the known planet, and transits of the additional planet. When they are found, what can transit measurements add to studies of multiplanet dynamical evolution? First, mutual inclinations become measurable, for comparison to the solar systems disk-like configuration. Such measurements will give important constraints to planet-planet scattering models, just as the RV measurements of eccentricity have done. Second, the Rossiter-McLaughlin effect measures stellar obliquity, which can be modified by two-planet dynamics with a tidally evolving inner planet. Third, TTV is exquisitely sensitive to planets in mean motion resonance. Two planets differentially migrating in the disk can establish such resonances, and tidal evolution of the planets can break them, so the configuration and frequency of these resonances as a function of planetary parameters will constrain these processes.
Planetary dynamics in multi-star systems

Many recent observational studies have concluded that planetary systems commonly exist in multiple-star systems. At least ~20% and presumably a larger fraction of the known extrasolar planetary systems are associated with one or more stellar companions. These stellar companions typically exist at large distances from the planetary systems (typical projected binary separations are within 100 - 10000 AU) and are often faint (ranging from F to T spectral types). Yet, secular cyclic angular momentum exchange with these distant stellar companions can significantly alter the orbital configuration of the planets around the primaries. One of the most interesting and fairly common outcomes seen in numerical simulations is the opening of the mutual inclination angle between the planetary orbits, forced by the differential nodal precessions caused by the binary companion. The growth of the mutual inclination angle between planetary orbits induces additional large-amplitude eccentricity oscillations of the inner planet due to the quadrupole gravitational perturbation by the outer planet. This eccentricity oscillation may eventually result in the orbital decay of the inner planet through tidal friction, as previously proposed as Kozai migration or Kozai cycles with tidal friction (KCTF). This orbital decay mechanism induced by the perturbation propagation from a stellar companion may stand as an alternative formation channel for close-in extrasolar planets.

Tide and hot Jupiters

Radial-velocity surveys show an apparent pile-up of hot Jupiters around 3 day orbital periods. Statistics from transiting surveys is still to come. Binary companions, coupled with tidal dissipation in the planets, can induce such a pattern. However, is binary really the answer?
On The Origins Of Eccentric Close-in Planets

Strong tidal interaction with the central star can circularize the orbits of close-in planets. With the standard tidal quality factor $Q$ of our solar system, estimated circularization timescales for close-in extrasolar planets are typically shorter than the lifetime of the host stars. While most extrasolar planets with small orbital radii ($a < 0.1$ AU) have nearly circular orbits, recent observations have revealed a handful of planets with substantially large orbital eccentricities. This new class of eccentric close-in planets implies that either the tidal $Q$ factor is underestimated, or the orbital circularization is prevented by other perturbation mechanisms. We constrain the tidal $Q$ factor for transiting extrasolar planets by comparing the circularization timescales with accurately determined stellar ages. Using the estimated secular perturbation timescales, we also provide constraints on the properties of hypothetical secondary planets exterior to the known eccentric close-in planets.
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Transits secondary eclipses of HD 189733 with Spitzer

We present limits on transit timing variations and secondary eclipse depth variations at 8 microns with the Spitzer Space Telescope IRAC camera. Due to the lack of limb darkening in the infrared and uninterrupted observing, Spitzer provides the highest accuracy transit times for this bright system, in principle providing sensitivity to secondary planets of Mars mass in resonant orbits. Some models of tidally-locked short-period hot Jupiters predict significant variability in the depth of secondary eclipse we compare the models to our Spitzer data. Finally, the transit data provides tighter constraints on the wavelength-dependent atmospheric absorption by the planet.

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Exoplanet spectroscopy at the tipping point

Molecules serve as powerful probes of the conditions, composition, and chemistry of exoplanet atmospheres. Using precision spectroscopy, it is possible to detect these molecules and provide the observations required for detailed, model-based, physical interpretations. Spectra of the primary and secondary eclipse events in transiting planets allow the crude spatial localization of molecular abundance estimates and thus probe the differences between the dayside and nightside atmospheres. Perhaps the most exciting aspect of the current work is that it anticipates a large number of measurements emerging over then next few months. In the future, applying these techniques to non-transiting planets is almost certainly feasible.
The discovery of extra-solar planets orbiting within a few tenths of an AU of their host stars has challenged our understanding of planetary formation and evolution. In particular, tides play an important role in changing the orbital and physical properties of these planets. Evidence for tidal evolution comes, for example, from the distribution of extra-solar orbital eccentricities: planets close to their host star tend to have smaller eccentricities than planets far from their host stars. We show that tidal evolution from orbits with a typical initial e distribution, farther out from the stars, can lead to the current close-in a and e distribution, a result with important implications for the processes of formation of planetary systems.

Since tides can change a planet's orbital elements, they can also affect the transit probability in important ways. Such effects depend sensitively on the physical properties of the star and planet, as well as on the system's age, potentially introducing observational biases that need to be considered in interpreting the statistics of transit discoveries. Tidal heating that accompanies orbital evolution can also have major effects on the physical properties of close-in planets, in many cases even dominating the heat budget of a planet. Interpretation of planetary radius measurements from transit observations must include the role of tidal heating. For example, the seemingly anomalous radius of HD 209458 b may be due to the substantial tidal heating during the planet's evolution.
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The planet atmosphere and exosphere: Emission and transmission spectroscopy

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Spectrum and atmosphere models of irradiated transiting extrasolar giant planets
Two Classes of Irradiated Atmospheres: A Unified Theory for the Atmospheres of the Hot and Very Hot Jupiters

The dayside atmospheres of hot Jupiter planets may naturally fall into two classes that are somewhat analogous to the M- and L-type dwarfs. Those that are warm enough to have appreciable opacity due to TiO and VO gases we term the pM Class planets, and those that are cooler we term pL Class planets. We calculate model atmospheres for these planets, including pressure-temperature profiles, spectra, and characteristic radiative time constants. We show that pM Class planets have hot stratospheres (temperature inversions) and may have large day/night temperature contrasts because atmospheric radiative timescales are much shorter than possible dynamical timescales. The pL Class planets absorb incident flux deeper in the atmosphere where atmospheric dynamics will more readily redistribute absorbed energy. This will lead to cooler day sides, warmer night sides, and larger phase shifts in thermal emission light curves. We interpret current secondary eclipse and light curve data in light of these models.

Characterizing the Atmospheres of Hot Jupiters: From Spectra to Multi-Color Maps

Hot Jupiters present a significant challenge for atmospheric circulation models, which indicate that day-night temperature differences on these heavily-irradiated planets may be as large as 1000 K. The amount of energy that is circulated from the perpetually-illuminated day side around to the night side has a significant influence on the properties of the planets atmosphere, including its equilibrium composition and day- and night-side pressure-temperature profiles. In particular, it has been suggested that planets hot enough to have gas-phase TiO or VO in their day-side atmospheres will form temperature inversions and have larger day-night temperature differences relative to planets at lower temperatures. We present new observations of the emission spectrum of TrES-4 designed to test this model by searching for the presence of a temperature inversion in a planet whose equilibrium temperature is well above the condensation point for TiO and VO. We also report new observations of the thermal phase curve of HD 189733b at 24 microns, which we combine with our previous observations at 8 micron to examine how circulation in this planets atmosphere varies as a function of depth. We discuss how the relatively small day-night temperature contrast on HD 189733b affects its observable properties, including its transmission and emission spectra.
The Atmospheres of Extrasolar Super-Earths

Extrasolar super-Earths (with masses in the range 1-10 M_Earth) are expected to be found in a range of orbits in the coming years. While a number of these planets have already been discovered through radial velocities and microlensing, it will be the discovery of the first transiting super-Earths that will open the door to a variety of follow-up observations aimed at characterizing their atmospheres. Super-Earths may likely fill a large range of parameter space in terms of their atmospheric composition and mass. Specifically, some of these planets may have high enough surface gravities to be able to retain large hydrogen-rich atmospheres, while others will have lost most of their hydrogen to space over the planets lifetime, leaving behind an atmosphere more closely resembling that of Earth or Venus. The resulting composition of the super-Earth atmosphere will therefore depend strongly on factors such as atmospheric escape history, outgassing history, and the level of stellar irradiation that it receives. Here we present theoretical models of super-Earth emission and transmission spectra for a variety of possible outcomes of super-Earth atmospheric composition, ranging from hydrogen-rich to hydrogen-poor. We focus on how observations can be used to differentiate between the various scenarios and constrain atmospheric composition.
3D Coupled Radiative Hydrodynamical Simulations of Irradiated Planetary Atmospheres

As has been demonstrated by several groups, three-dimensional hydrodynamical models including radiative energy transfer are crucial components for the modeling of irradiated planetary atmospheres. Recent improvements to our techniques allow for the simultaneous solution of both the radiative and hydrodynamical energy equations. Such an approach allows for the detailed study of the role of both absorption and emission opacities while still solving the full Navier-Stokes equations. I will present resulting energy distributions and predicted spectra and light curves from a suite of such models to address the role of irradiation levels, interior structure, planetary rotation, and atmospheric opacities.
Energetic neutral atoms as the explanation for the high velocity hydrogen around HD 209458b

Absorption in the stellar Lyman-alpha line observed during the transit of the extrasolar planet HD 209458b reveals high velocity atomic hydrogen at great distances from the planet. This has been interpreted as hydrogen atoms escaping from the exosphere of the planet, possibly undergoing hydrodynamic blow-off, being accelerated by stellar radiation pressure. However, around solar system planets the production of energetic neutral atoms from charge exchange between solar wind protons and neutral hydrogen from the exospheres has been observed, and should also occur at extrasolar planets. Here we show that the measured transit-associated Lyman-alpha absorption can be explained by the interaction between the exosphere of HD 209458b and the stellar wind, and that radiation pressure alone cannot explain the observation. This is the first observation of energetic neutral atoms outside the solar system. Since the stellar wind protons are the source of the observed energetic neutral atoms, this provides a completely new method of probing stellar wind conditions, and our model suggests a slow and hot stellar wind near HD 209458b at the time of the observation.
The NASA EPPOXI Mission of Opportunity to Gather Ultraprecise Photometry of Known Transiting Exoplanets

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The NASA Discovery mission EPOXI, utilizing the Deep Impact flyby spacecraft, is comprised of two phases: EPOCh (Extrasolar Planet Observation and Characterization) and DIXI (Deep Impact eXtended Investigation). EPOCh will use the 30-cm high resolution visible imager to obtain ultraprecise photometric light curves of known transiting planet systems. These data will be analyzed for evidence of additional planets, via transit timing variations or transits for planetary moons or rings for detection or constraint of geometric albedos and for refinement of the system parameters. Over a period of four months, EPOCh aims to observe five known transiting planet systems, with each system to be observed continuously for several weeks. Here we present an overview of EPOCh, including the spacecraft, motivations and science goals, and preliminary photometry results.
Serendipitous Detection of Transiting Planets in Future Synoptic Surveys

Over the next decade, many surveys will be coming on line that will monitor significant fractions of the sky to various depths with various cadences. I discuss the prospects for the serendipitous detection of transiting planets in these synoptic time-domain surveys. I first discuss general considerations regarding the survey areas, cadences, photometric properties, and depth, and how these impact the detectability of transiting planets. I then go on to discuss the expected yields for particular surveys, including SDSS-II, Pan-STARRS, and LSST. I discuss a worked example of a low-mass eclipsing binary that was originally detected with sparse but precise SDSS-II photometric data, which serves to illustrate the difficulties with the follow-up and confirmation of candidate transiting planets with such data. I finally speculate on the prospects for confirming the hundreds or thousands of transiting planets that are expected from these surveys.

The Pan-Planets Project - A massive Search for Hot Jupiters

An ambitious search for transiting extrasolar planet will be performed with the 1.8-m Pan-STARRS1 telescope and the largest camera in the world (7 square degrees), starting end 2008. The telescope is located at the Haleakala Observatory in Maui, Hawaii. Pan-Planets has an exceptional potential for a transit search of close-in Jupiter-like planets (0.1 AU), since it combines a large field of view, a significant telescope size, with a fast read-out of the CCD camera (few seconds), and a quick slew of the telescope. These features allow the monitoring of several hundred thousand stars in only one field, and million of stars in two or more fields. Pan-Planets is expected to provide 100 Jupiter-like planets.
Prospects for Transits From Space: Detailed Characterization and Future Surveys

A vital aspect of the scientific benefit of transiting planets is the wealth of information obtainable through detailed follow-up observations. I discuss opportunities for physical characterization of planets found through present and future transit missions.

Transiting Exoplanet Survey Satellite (TESS)

The Transiting Exoplanet Survey Satellite (TESS) is a low cost, SMEX-class planet finder. In a two-year all-sky survey, TESS will observe more than two million bright nearby stars, searching for temporary drops in brightness that are the signatures of planetary transits. TESS is expected to catalog more than 1000 transiting exoplanet candidates, including a sample of Super Earths. The TESS wide-shallow survey will be complementary to the narrow deep ones of the Corot and Kepler missions: its sky coverage will exceed that of Corot by 2000 times, and that of Kepler by 400 times. Because the TESS survey will systematically examine the entire sky for bright stars likely to harbor an exoplanet, the resulting TESS Transit Catalog will constitute a unique scientific legacy. High resolution, follow-up ground-based optical and space-based IR spectroscopy of exoplanets demands bright targets. Thus, TESS should identify those new exoplanets that are ideal for detailed photometric and radial velocity followup studies with the largest ground-based telescopes in the visible band (e.g. HARPS and HARPS-NEF), as well as atmospheric studies with NASA's upcoming James Webb Space Telescope in the IR band. The TESS mission is a collaborative effort by researchers at MIT, the Harvard-Smithsonian Center for Astrophysics, and the NASA Ames Research Center. It is proposed for launch in early 2012.