Observations of transiting exoplanets

Last year, exoplanet discoverers were finally rewarded with half a Nobel Prize in Physics, for the development of radial-velocity exoplanet detection, and for the discovery in 1995 of an exoplanet hosted by a normal main-sequence star, 51 Pegasi b (Mayor 2019, Queloz 2019). Radial velocity data demonstrated that objects like 51 Peg b were extremely likely to be of giant-planetary mass, unless the orbital orientation were very close to face on. The dimensions of planetary orbits are such that they are beyond our ability to resolve spatially except in special cases, so there was no way for the observers to tell what the inclination of the 51 Peg system is. Of course, the large number of planets discovered in the ensuing years made it extremely unlikely that *all* such objects were in face-on orbits, therefore merely being faint stars. But everyone still breathed easier when one of the radial-velocity planets, HD 209458 b, was seen to transit its host star (Charbonneau et al. 1999, Henry et al. 2000). A planet's orbital plane has to be viewed pretty close to edge-on for the planet to transit the star. Knowing this much about the orientation improved the uncertainty in the planet's mass to a few percent, proving that it is of Jovian mass. The magnitude of diminution of the stellar flux during the transit showed that the planet is also of Jovian size. The derived mass and radius revealed that the planet is furthermore of Jovian bulk density, and thus a gas giant. Thus began the study of the diversity of exoplanets: the combination of radial velocity and transiting observations yield planetary mass and bulk density as well as orbital elements, and can distinguish between Jovian, Neptunian, and rocky planets.

HD 209458 b came as no surprise, least of all to Bill Borucki. He had been trying for decades, long before the radial-velocity planet discoveries, to initiate and raise money for a NASA satellite observatory which would search for exoplanetary transits across their host stars. He and his team had long since worked out solutions to the challenging photometric-accuracy problems at a level that would enable detection of planets as small as Earth, even down to Mercury-size; that could offer photometric stability over long enough times to detect planets orbiting in the zones around their stars in which liquid water would be stable on solid planetary surfaces; that could search several hundred thousand stars in order to find tens of thousands of transiting systems; that could automatically characterize light curves well enough to eliminate false alarms such as those from grazing binary-star eclipses or stellar oscillation; and that could attract a diversity of astrophysicists who would also be willing to study the many other stellar-variability projects that would be done unprecedentedly well by the same satellite observatory. Borucki's Discovery-class mission, *Kepler* and its extension *K2*, delivered essentially perfectly on all these promises, discovering thousands of exoplanets and tens of thousands of other good candidates. Soon there also developed many small ground-based telescope networks, and another satellite observatory (TESS), to search for planetary transits more widely in the sky than the *Kepler* and *K2* fields, and more widely among brighter stars. *Kepler* had also been beaten into orbit by three years, by the ESA mission *CoRoT*, which was originally designed primarily to observe stellar oscillation and convection but also joined the search for exoplanet transits. *Kepler*, however, discovered more than the others combined.

Nowadays, transits are the main exoplanet detection method, and radial velocity the followup to complete the planetary mass measurement. The lion's share of the planets, and by far the best light curves, come from *Kepler* and *K2*. Borucki's mission proved the ubiquity of planetary systems; it began and still leads the study of the diversity of planetary systems.

In this project, you will confirm at least one exoplanet and measure its orbital period:

- using the handy Swarthmore transit predictor, find the stars that are up at night this semester. Note that Mees is one of the options on the transit predictor's menu of observatories. You may also find the NASA Exoplanet Archive to be helpful.
- find the ones with the largest eclipse contrast; that are bright enough not to require exposures longer than five minutes in L for high signal-to-noise; and that have relatively short orbital periods,

thus to provide numerous opportunities to observe multiple transits. Note that brighter is not necessarily better. Generate a rank ordered list of your candidates.
- use the transit predictor on these candidates to determine the nights on which their transits would be visible, making sure that you have a large enough selection to cover many nights.
- plan a cadence of observations so that each transit is well sampled, and that can be sustained for a an hour or so on either side of the transit. Plan to use the L filter except for very bright host stars.
- take great care with photometric measurements; in particular, make sure that your photometry gives the same magnitude in every measurement, for every potential reference star in the same field as your planet host star.
- once detected, confirm the transit at least once, preferably the next transit (weather permitting).
- characterize the uncertainty of each photometric point, well enough to sustain simple model fitting.

In your analysis, answer the following questions for each exoplanet whose transits you observe:

- From your data, what is the orbital period of the planet, and what are the radii of the star and the planet? What is the planet's orbital inclination likely to be? Take account of stellar limb darkening in your answer.
- How do you know that this is a planetary transit, and not some other effect such as stellar variability, a starspot, or a partial eclipse in a binary star system? Prove it.
- Suppose the host "star" were really an unresolved binary star with an orbital period of several years, and the transiting planet in orbit around one of them. What effect would this have on your determination of the planet's radius? How could such multiplicity be detected? Given the distance to your exoplanet's host star, what constraints can be placed on its multiplicity, from current observations?
- Considering the size and the orbit that you measure, what kind of planet is this? What are its surface conditions likely to be? Might it be habitable?
- Is it likely to have formed in the orbit in which you see it? How do you know?
- Did you reach the photometric accuracy that you expected? If not, why not?
- After that analysis: how do your results compare to other results on this exoplanetary system?

Include with your report a good image of your planet-host(s)'s field, and good, calibrated, phase-folded renditions of the transit light curves with errorbars. Archive these, and all of your raw and reduced data, on the Astronomy Lab data drive.

Additional reading

Astronomy 111: lectures 25, 26.

Astronomy 241: class 5.

Stellar limb darkening: AST 241 above, or Mandel & Agol 2002, ApJL, 580, L171-L175.

Exoplanet statistics: Winn & Fabrycky 2015, ARA&A 53, 409-447.

Design of transit experiments from space and from the ground: Borucki 2016, Rep. Prog. Phys. 79, 036901 (*Kepler*), and Kane et al. 2005, MNRAS 362, 117 (SuperWASP), respectively.