Problem Set #2

Due Monday, September 25 at 5pm

Please indicate the time spent on the assignment and list any collaborators. You can submit the assignment by emailing a single PDF to dressing@berkeley.edu or by placing a hard copy in my mailbox or under my door (Campbell 605E).

1. Microlensing

The website *Microlensing Source* contains several tutorials about microlensing as well as interactive tools. Go to the interactive section (`http://microlensing-source.org/interactive/86/`) and perform the following exercises:

a. Using the "single lens" tool, produce a lightcurve for the microlensing of a $0.5\,\mathrm{M}_{\odot}$ star at a distance of 4 kpc by a source star at a distance of 8 kpc. Choose your own values for the other input parameters. Click the "play" button to watch the microlensing event and write a few sentences describing the animation. State the values you chose for the input parameters and explain how each term affects the resulting microlensing lightcurve. Include a screenshot of the animation and label the lines and points on the graph.

b. Vary some of the input parameters in your single lens model. Describe which parameters you changed and discuss any changes to the resulting animation.

c. Now use the "binary lens" tool to simulate the microlensing detection of an exoplanet. Adjust the lens masses so that lens mass 1 is a star and lens mass 2 is a planet. Run three simulations using different impact parameters. As in part (a), take a screen shot of the simulation and label the figures. State the input parameters you selected for each simulation and explain why your simulated lightcurves and magnification maps have different morphologies.

2. Radial Velocity

An astronomer has been collecting radial velocity observations of a nearby star with a mass of $0.75\,\mathrm{M}_{\odot}$. She reports a signal with a semi-amplitude $K = 2.4$ m s^{-1} and a period of 7 days. The orbit appears to be circular, but the inclination of the planet is unknown.

a. What is the minimum mass of the planet?

b. Assuming that inclination angles are randomly distributed, what is the most likely mass of the planet? How does this compare to the answer you found in part (a)?

c. Consulting Section 2.4 of the radial velocity chapter of *Exoplanets*, describe three different sources of stellar noise. How do the amplitudes and timescales of the RV signals caused by those phenomena compare to the signal detected by the astronomer?

3. Radial Velocity Part 2: How do we look to the neighbors?

a. An alien astronomer has been monitoring the radial velocity of the Sun for the last 25 years. Assuming that the astronomer is able to detect signals with amplitudes larger than 5 m s^{-1}, which planets might they be able to detect? How large are the RV perturbations caused by those planets?

b. Neglecting the Sun's systemic velocity, plot the radial velocity of the Sun for the last 25 years. You may ignore any planets that the alien astronomer would have missed. Assume that the alien astronomer acquired 500 observations randomly spaced in time and include their observations on your plot. The alien's data should be noisy and plotted with error bars.

c. Produce a phase-folded plot of radial velocity versus orbital phase for each of the planets that the alien might have detected. Include both the Sun's actual radial velocity and the alien's data. You may wish to subtract off the signals of the other planets.

4. *Transit*

a. Draw a cartoon view of a planetary transit and the resulting lightcurve. Label both diagrams and write a few sentences explaining how the properties of the planet could be determined if the host star had already been characterized.

b. Assuming $e = 0$, compute the geometric likelihood of transit, the transit duration, the transit depth, and the transit duty cycle (fraction of total orbit during which the planet is transiting) for the following star/planet pairs:

(i) Jupiter-sized planet orbiting a Sun-like star with $P = 1$ day and $b = 0.3$

(ii) Earth-sized planet orbiting a Sun-like star with $P = 365$ days and $b = 0.1$

(iii) Neptune-sized planet orbiting a K dwarf ($0.7\ \mathrm{M}_\odot$, $0.7\ \mathrm{R}_\odot$) with $P = 800$ days and $b = 0.4$

(iv) Earth-sized planet orbiting an M dwarf ($0.3\ \mathrm{M}_\odot$, $0.3\ \mathrm{R}_\odot$) with $P = 42$ days and $b = 0$

(v) Earth-sized planet orbiting an M dwarf ($0.3\ \mathrm{M}_\odot$, $0.3\ \mathrm{R}_\odot$) with $P = 42$ days and $b = 0.9$

c. Qualitatively, how would your answers to part (b) change if the planets had eccentric orbits? Which formulae would you need to use?

d. *For experienced programmers:* Download and install Laura Kriedberg's `batman` Python package (`http://astro.uchicago.edu/~kreidberg/batman/`). After completing the tutorial, use the values reported by Charbonneau et al. (2000, ApJ, 529, 45) to produce a transit lightcurve for HD 209458 b. Compare your model lightcurve to their Figure 2. As part of your write-up, please list the input parameters you used when calling `batman` and describe any assumptions.

e. *For experienced programmers:* Assume that a space-based observatory measured the brightness of HD 209458 every 30 minutes for 90 days total with a single measurement precision of 50 ppm. Now conduct the following steps:

(i) Simulate a set of observations.

(ii) Overplot the observations on the "true" transit model you found in part c.

(iii) *Challenge Problem:* Using the method of your choice (e.g., scipy Levenberg-Marquardt least-squares minimization), fit a transit model to your simulated observations. Comment on how well your solution matches the actual input parameters. Which transit parameters are the hardest and easiest to recover?

(iv) *Challenge Problem:* Run a Markov chain Monte Carlo analysis to determine the errors on your fitted transit parameters. What is the level of agreement between your fitted values and the input values for each parameter? You may wish to use Daniel Foreman-Mackey's `emcee` package (`http://dan.iel.fm/emcee/current/`).