Task 6

Detection of extrasolar planets

The search for extrasolar planetary systems is a popular topic in modern astrophysics. In principle there are a large number of possible ways to discover planetary companions of nearby stars. In this task you will get familiar with the requirements on some important observational techniques to detect extrasolar planetary systems. Physical insight is more important than precision (usually one significant digit is enough).

Questions:

1.) Which possibilities for detecting planetary systems can you think of? (it is very useful to think about this question carefully before you continue)
2.) Which properties of stars could have an influence on the probability that they have a planetary system?
3.) Planets can have a wide range of properties. Which independent parameters do you expect to be most important for the different detection methods? (again, it is very useful to think about this question carefully before you continue)

To simplify matters, in the following we assume the existence of one single planet in a circular orbit.

1. Astrometry

The barycenter of a star moves around the center of mass of the star–planet system. The resulting orbital motion reveals the existence of a companion, in analogy to binaries.

Questions:

4a) Which orbit would the Sun describe if our solar system consists of the central star and one planet? Calculate the orbital radius and period assuming that the planet is:

   i. the Earth,

   ii. Jupiter,

   iii. a "hot Jupiter" at a distance of 0.05 AU.

4b) Assume that each of the systems mentioned in question 4a) is studied from a distance of 20 pc. Which orbits (in units of arcseconds) result from the three cases for an observer on Earth?

4c) Compare your results from 4b) with the accuracy that can be achieved in astrometric observations from the ground and from space.

2. Spectroscopy

The motion of the central star discussed in questions 4a-c) is not only detectable astrometrically, but also spectroscopically using the Doppler shift.

Questions:

5a) Which measurements do you have to perform in this case? Assume you want to observe the systems mentioned in question 4b). Which velocities will be observed? Determine the Doppler shift for the three cases under the assumption that you observe at optical wavelengths (about 500 nm).

5b) Which spectroscopic precision is necessary to measure the effect estimated in 5a)? Compare this with the widths of the absorption lines in the solar spectrum (see e.g. Photometric Atlas of the Solar Spectrum, Utrecht) and with the spectral resolution of typical astronomical spectrographs.

5c) For the measurements discussed in 5b) it is not only necessary to achieve high resolution but also a stable calibration of the wavelength scale. How could you do that? Are spectra of the night sky or twilight sky suitable for this task? Which other possibilities can you think of?

3. Photometry

Planets reflect the light of the central star. Hence they are in principle directly observable in extrasolar planetary systems, too (in analogy to visual double stars). Moreover, they can be discovered as they block the light of the central star during a transit across the stellar disk (like eclipsing binaries), if a suitable inclination of the orbit with respect to the line of sight is given.

Questions:

6a) How bright are the three planets given in 4a) at a distance of 20 pc? Compare with limiting magnitudes of astronomical observations and with the brightness of the central star.

6b) Direct observations are difficult not only because of the absolute magnitudes of the planets but also because they are close to the central star. Describe the image of the central star observed with a diffraction-limited 2.5 m telescope. Compare the radial function $I(r)$ for this telescope with your results from 6a). How does this compare to the situation of the point spread function of a ground-based telescope? Assume that the atmospheric turbulence ("seeing") leads to a profile which can be described by a Gaussian distribution with a half-light diameter of $1''$.

6c) How long does the transit of a planet across the stellar disk last (in hours, in fraction of the orbital period) in the three cases in question 4a)? Assume the observer to be at a large distance in the plane of the planet's orbit. How large is the change in brightness of the central star during the partial occultation in all three cases? Sketch the "light curve" of the whole system during one complete orbital period.

6d) You want to observe the transits discussed in 6c). Assume that all stars have exactly one planet as large as Jupiter and placed at a distance of 5.2 AU. The orientation of the orbital planes are distributed randomly. How large is the percentage of stars for which transits are observable thanks to proper inclination of the orbital plane with respect to the line of sight? Assume now that the space density of stars with these types of planetary systems (at any orientation) is $10^{-3}\,\mathrm{pc}^{-3}$. What is the expected distance of the nearest observable system? How bright would the Sun be at this distance?

6e) For the observation of 6d) you use an ideal detector (100% efficiency, no instrumental noise). The observation should be performed by a space telescope (no background, no atmospheric disturbances). The only source of noise is the statistical photon noise. How long do you need to expose with a telescope with an aperture of 1 m in order to determine the difference of the brightness of the star before and during the occultation as a 5σ signal when the bandwidth of your instrument is 100 nm (e.g. V band: 450 nm - 550 nm)? Are the assumptions realistic? Which modifications result if the experiment is done from the ground?