

# Mini-Review on Exoplanet Detection Methods

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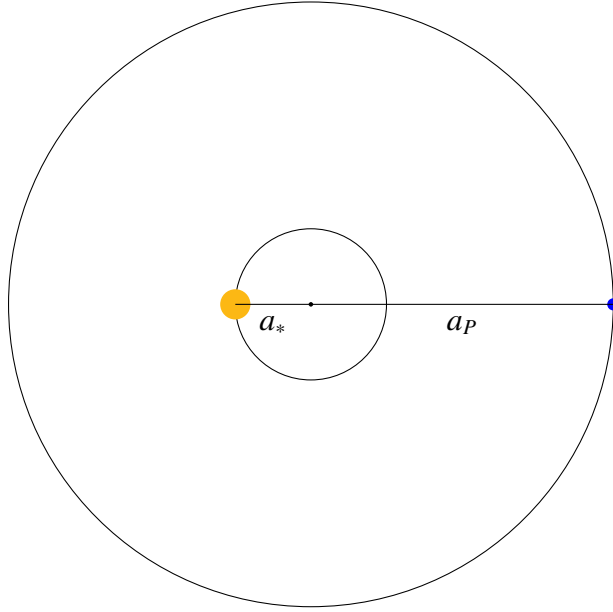
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Exoplanets, connected as they are to the search for life on other planets, are an attractive topics to students of all ages. Detecting them, however, is a challenge. Most exoplanets have only been detected indirectly. The indirect methods are based on concepts and phenomena that are accessible to school students, and this mini-review gives a bare-bones account of those methods.

The methods reviewed here are the “classical” detection methods: the radial velocity method and the transit method. Beyond the basics presented here, there are interesting new developments afoot: With the planned fourth data release (DR4) of the Gaia mission of the European Space Agency ESA, the astrometric detection method, where an exoplanet’s orbit is estimated from the host star’s minute shifts in the night sky, is likely to become more important. Over the past few years, measurements with the James Webb Space Telescope of spectra, extracted both from direct observations and from exoplanet transits, have opened up a whole new field of atmospheric studies of exoplanets. With the upcoming start of NASA’s Roman Space Telescope later this year, direct observations will become more important: Roman has a coronagraph on board, which will allow for direct observations of planets while “blotting out” the light of the central star.

## 1 Star and Planet in mutual orbit

Consider a star with mass  $M_*$  and a planet with mass  $M_P$  orbiting each other. Note that this differs from how we usually view the Solar System: there, more often than not, we assume the Sun to be stationary in the center, and the planets orbiting around it. For exoplanet detection, it is important that both star and planet orbit their common center of mass. For simplicity, we assume that both bodies move on circular orbits; in the following image, the geometry is viewed “face-on,” directly from above:



Let  $a_p$  be the (constant) distance of the planet from the joint center of mass, and  $a_*$  the corresponding distance for the star. The star and planet are always on exactly opposite sides of the central point, so they share the same orbital period  $P$ . Their orbital speeds are therefore

$$v_* = \frac{2\pi a_*}{P} \quad \text{and} \quad v_p = \frac{2\pi a_p}{P}. \quad (1)$$

Each is equal to the circumference of the orbit, divided by the orbital period.

The strength of the gravitational force between the two bodies is given by Newton's famous inverse-square law of gravity:

$$F_G = \frac{GM_*M_p}{(a_* + a_p)^2}. \quad (2)$$

Circular motion implies that the star experiences a centripetal acceleration toward the center of mass, with magnitude

$$b_{\text{centripetal}} = \frac{v_*^2}{a_*} = 4\pi^2 \frac{a_*}{P^2}. \quad (3)$$

This acceleration is caused by the gravitational force, so by Newton's second law, force equals mass times acceleration, we must have

$$4\pi^2 \frac{a_*}{P} = \frac{1}{M_*} \frac{GM_*M_p}{(a_* + a_p)^2}, \quad (4)$$

which can be simplified to

$$a_* M_* = \frac{P^2}{4\pi^2} \frac{GM_* M_P}{(a_* + a_P)^2}. \quad (5)$$

By the same reasoning, we obtain the analogous equation for the planet:

$$a_P M_P = \frac{P^2}{4\pi^2} \frac{GM_* M_P}{(a_* + a_P)^2}. \quad (6)$$

From these two equations, we immediately obtain

$$a_* M_* = a_P M_P. \quad (7)$$

This should not come as a surprise. After all, the star and planet orbit around their common center of gravity, which implies directly that distances from this center must be inversely proportional to their masses,

$$\frac{a_*}{a_P} = \frac{M_P}{M_*}. \quad (8)$$

This is exactly analogous to the situation of two persons on a seesaw: for the seesaw to be horizontal, the heavier person must sit closer to the fulcrum.

We can readily derive the Kepler's third law for our setup: Divide equation (5) by  $M_*$  and equation (6) by  $M_P$ , then add the results:

$$a_* + a_P = \frac{P^2}{4\pi^2} \frac{G(M_* + M_P)}{(a_* + a_P)^2}. \quad (9)$$

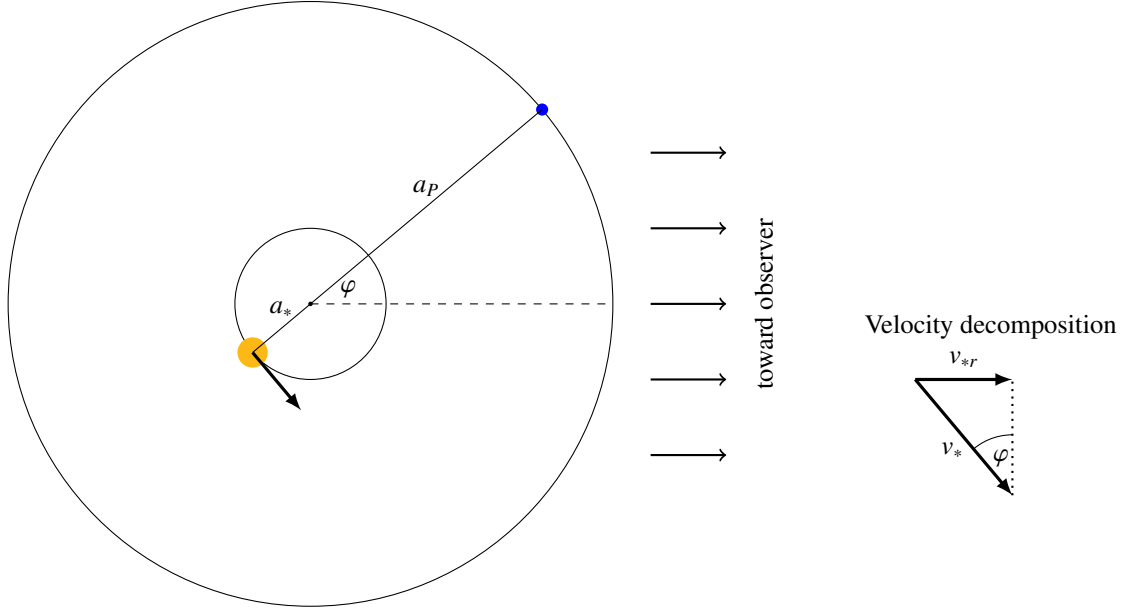
Collecting all terms containing  $a_*$  and  $a_P$  on the left-hand side, we have

$$(a_* + a_P)^3 = \frac{G(M_* + M_P)}{4\pi^2} P^2, \quad (10)$$

which is Kepler's third law in the Newtonian form, with the proportionality constant given explicitly in terms of the total mass.

## 2 Radial Velocity

The radial velocity of the star can be measured via the Doppler effect: well-defined spectral lines of the star shift toward the red end of the spectrum when the star moves away from us, and toward the blue end when it moves toward us. If we were viewing the orbital plane edge-on, the radial velocity would depend only on the star's orbital speed  $v_*$  and the orbital position angle, as illustrated in this sketch:



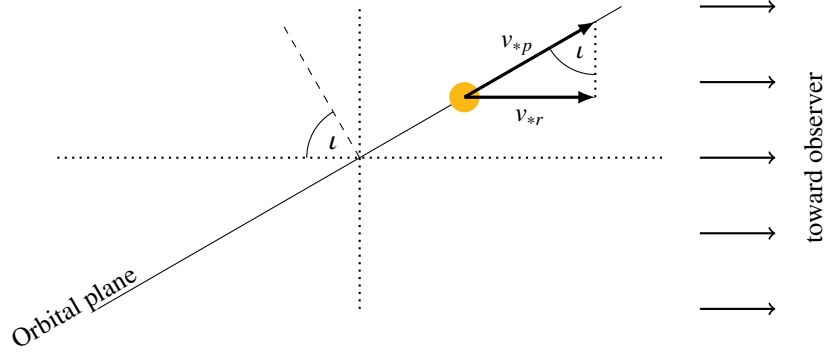
In the sketch, the observer is far away towards the right. The radial velocity  $v_{*r}$  is the component of the star's velocity projected onto the line of sight from the system's center of mass to the observer; in our diagram, this is the horizontal direction. As shown in the velocity decomposition inset on the right, we have

$$v_{*r} = v_* \cdot \sin(\varphi). \quad (11)$$

The orbital angle  $\varphi$  changes with time as

$$\varphi(t) = \frac{2\pi}{P} \cdot t + \varphi_0, \quad (12)$$

so the radial velocity varies sinusoidally with time. If the orbital plane is not viewed edge-on, but inclined relative to the line of sight, an additional (constant) geometric factor appears. The next figure shows the orbital plane and the direction to the observer from the side. The angle  $\iota$  (lowercase Greek letter iota) is called the *inclination* or *orbital inclination*.



For  $\iota = 90^\circ$ , the observer sees the orbital plane edge-on; for  $\iota = 0^\circ$ , the observer sees it face-on.

The quantity  $v_{*p}$  is the velocity component in the orbital plane. As the vector diagram shows, the orbital inclination introduces an additional factor of  $\sin \iota$ . The radial velocity thus takes the form

$$v_{*r} = v_* \sin \left[ \frac{2\pi}{P} \cdot t + \varphi_0 \right] \cdot \sin \iota. \quad (13)$$

### 3 Radial Velocity Method

For most exoplanetary systems, it is impossible to obtain a resolved image, that is, an image that shows the star, the planet and their mutual separation. Instead, we only “see” the star itself, and any deductions about the presence of a planet need to be made from measurements on the host star only. The planet is typically invisible with current technology (a helpful simile: the brightness ratio between star and planet is like trying to detect a firefly next to a stadium spotlight from several kilometers away).

In many cases, the star’s radial velocity can be detected via the Doppler effect, as we have examined in the preceding section. In the simplest case, with only one planet present, the radial velocity varies periodically. From this, we can determine an important observational quantity: the orbital period  $P$ .

The radial velocity method exploits this phenomenon. By measuring the Doppler shift, we can reconstruct the velocity curve (13) and thus determine the quantity  $v_* \cdot \sin \iota$ .

You can interactively explore the fundamental setup in the browser-based app accessible under the following URL, adjusting key parameters and observing how the radial velocity curve changes:

<https://astro-apps.org/RadialVelocityMethod/index.html>

For a systematic analysis of what the Doppler curve can tell us about the planet, it is important to express  $v_*$  in terms of other system parameters. From (8), we have

$$(a_* + a_P) = \frac{a_*}{M_P}(M_* + M_P). \quad (14)$$

We can replace  $a_*$  with  $v_*$  using equation (1). Substituting the result into Kepler's third law (10) yields

$$v_* = \left(\frac{2\pi G}{P}\right)^{1/3} \frac{M_P}{(M_* + M_P)^{2/3}}. \quad (15)$$

We can rewrite this expression in a way that makes the orders of magnitude directly visible:

$$v_* \approx 100 \text{ m/s} \left(\frac{M_P}{M_J}\right) \cdot \left(\frac{10 \text{ days}}{P}\right)^{1/3} \cdot \left(\frac{M_* + M_P}{M_\odot}\right)^{-2/3} \quad (16)$$

$$\approx 10 \text{ cm/s} \left(\frac{M_P}{M_\oplus}\right) \cdot \left(\frac{1 \text{ year}}{P}\right)^{1/3} \cdot \left(\frac{M_* + M_P}{M_\odot}\right)^{-2/3}. \quad (17)$$

Here,  $M_J$  is the mass of Jupiter and  $M_\oplus$  is the mass of Earth. The best current spectrographs can detect radial velocities of  $\sim 1 \text{ m/s}$  (HARPS, CARMENES). No wonder that this method initially discovered many hot Jupiters (that is, massive planets that are comparatively close to their stars).

By analyzing the time dependence of the radial velocity (13), we can determine the amplitude  $v_{*a} = v_* \cdot \sin \iota$ . We can solve the resulting expression for  $M_P \cdot \sin \iota$  using formula (15) to yield

$$M_P \cdot \sin \iota = v_{*a} \cdot (M_* + M_P)^{2/3} \left(\frac{P}{2\pi G}\right)^{1/3} \approx v_{*a} \cdot M_*^{2/3} \left(\frac{P}{2\pi G}\right)^{1/3}. \quad (18)$$

The approximation in the final step is valid because planetary masses are typically much smaller than stellar masses. (In our solar system, the Sun has more than a thousand Jupiter masses.)  $v_{*a}$  and  $P$  are measurable. The stellar mass can be inferred from the spectrum of a (main-sequence) star.

Thus, the radial velocity method provides an estimate for  $M_P \cdot \sin \iota$ . Since  $\sin \iota$  ranges from 0 to 1,  $M_P \cdot \sin \iota$  sets a lower bound on the planet's mass  $M_P$ .

## 4 Transit Method

If by chance we see a given exoplanet system edge-on or nearly edge-on, there is another way of indirectly detecting the planet: the transit method, which detects planets indirectly by observing periodic changes in brightness as an observer on Earth sees the planet pass in front of its host star.

You can interactively explore the fundamental setup and see how the transit light curve changes as a function of the system's fundamental parameters in the browser-based app available under the following URL:

<https://astro-apps.org/TransitMethod/index.html>

The following quantitative analysis presents simplified versions of the calculations from the paper Seager and Mallén-Ornelas 2002. The first formula relating the parameters is straightforward: in most cases, the planet's disk passes completely in front of the star's disk during a transit. In the light curve, this shows as a nearly flat stretch near the brightness minimum, corresponding to the time when the planet is fully in front of the star. To first approximation, assuming each region of the stellar disk appears equally bright (which is not strictly true due to limb darkening), the fractional decrease in flux  $\Delta F$  is

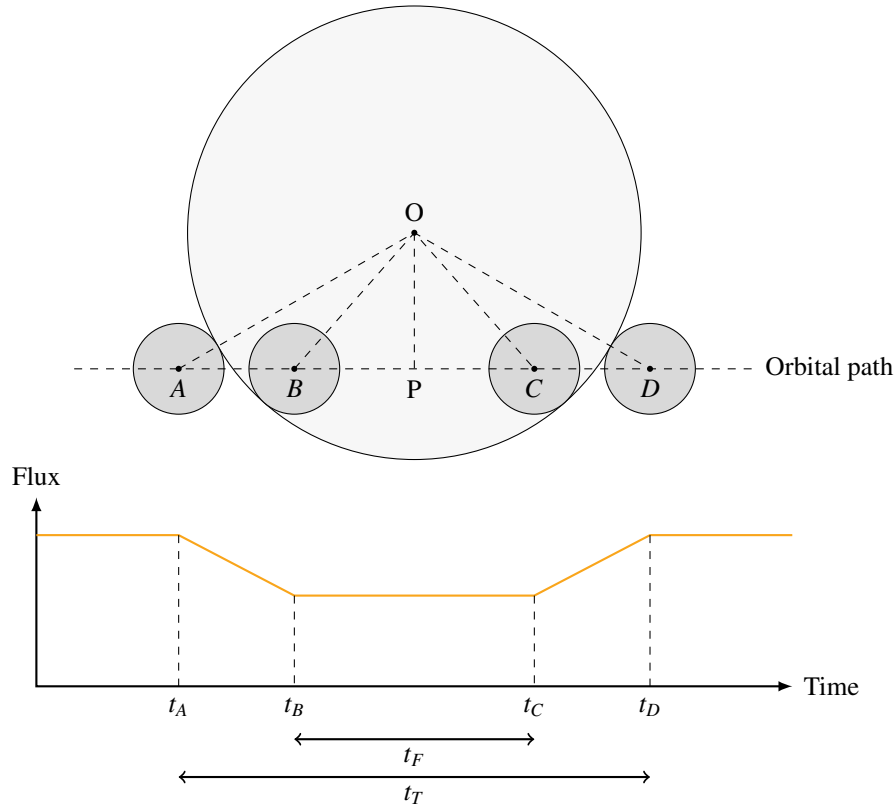
$$\Delta F = \frac{F_{\text{without transit}} - F_{\text{during transit}}}{F_{\text{without transit}}} \quad (19)$$

which equals

$$\Delta F = \left( \frac{R_p}{R_*} \right)^2, \quad (20)$$

where  $R_p$  is the planet's radius and  $R_*$  is the star's radius. This is simply the ratio of the planet's cross-sectional area  $\pi R_p^2$  to the star's cross-sectional area  $\pi R_*^2$ , i.e., the fraction of the star's disk obscured by the planet. The star's radius can be inferred from its spectrum and standard models of stellar structure. With this additional information, the observed flux change and formula (20) directly yield the planet's radius  $R_p$ .

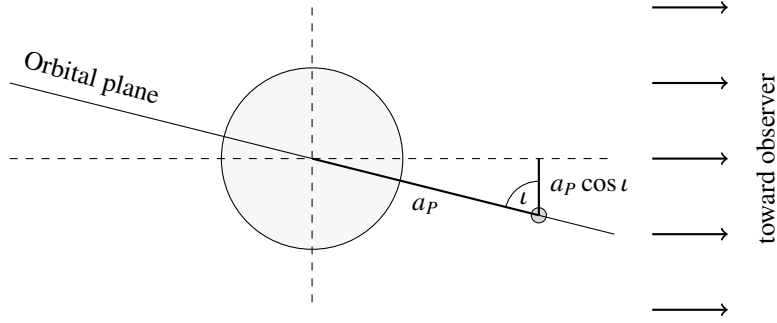
From the durations of the ingress and egress phases and the duration of the minimum, further inferences can be drawn. The following diagram shows the planet's disk at different positions in front of the star's disk—note that we cannot see this detail in real exoplanets; we infer it from the light curve:



In this figure, the upper part shows the view from Earth if we had an extremely high-resolution telescope—the (brighter) stellar disk and four positions  $A$ ,  $B$ ,  $C$ , and  $D$  of the planet's disk as it moves from left to right. The lower part shows the light curve—the change in the star's brightness over time from our perspective. The times when the planet's disk is at positions  $A$ ,  $B$ ,  $C$ , and  $D$  are marked. Qualitatively, the curve is straightforward: before reaching position  $A$ , the star has its normal brightness. Starting at  $A$ , the planet begins to transit, and the brightness decreases—by an amount exaggerated by a factor of 10 here for clarity. At position  $B$ , the planet is fully in front of the star, and the minimum brightness phase begins. This continues until position  $C$ , after which the planet starts to move out from behind the star, until at position  $D$  it no longer obscures any part of the star, and the star returns to its original brightness.

We can describe this process quantitatively using simple trigonometry. The orbital segment from  $A$  to  $D$  can be approximated as a straight line, shifted vertically by the inclination  $\iota$ . First, calculate the spatial distances of the planet's disk center from the reference point  $P$ . Triangle  $\triangle APO$  is right-angled. The length of

leg  $OP$  is  $\overline{OP} = a_P \cos \iota$ , where  $a_P$  is the orbital radius and  $\iota$  is the inclination relative to Earth-based observers. This is easiest to see by viewing the system from the side, as schematically shown:



The distance  $OA$  equals the sum of the stellar and planetary radii, so  $\overline{OA} = R_* + R_P$ . With two sides of the right triangle known, we can compute the third using the Pythagorean theorem:

$$\overline{PA} = \sqrt{(R_* + R_P)^2 - (a_P \cos \iota)^2}. \quad (21)$$

By symmetry,  $\overline{PD} = \overline{PA}$ . Similarly, for the right triangle  $\triangle BPO$ , we find

$$\overline{PB} = \sqrt{(R_* - R_P)^2 - (a_P \cos \iota)^2}. \quad (22)$$

Again, by symmetry,  $\overline{PB} = \overline{PC}$ . The flat part of the light curve between positions  $B$  and  $C$  is traversed in time  $t_F$ , corresponding to an orbital path length of

$$\overline{BC} = \overline{PB} + \overline{PC} = 2 \sqrt{(R_* - R_P)^2 - (a_P \cos \iota)^2}. \quad (23)$$

For a circular orbit (and for simplicity, we consider only circular orbits in this guide), the orbital speed is constant:  $v_P = 2\pi a_P / P$ . Thus, the time to traverse  $\overline{BC}$  is

$$t_F = \frac{\overline{BC}}{v_P} = \frac{P}{\pi a_P} \sqrt{(R_* - R_P)^2 - (a_P \cos \iota)^2} = \frac{PR_*}{\pi a_P} \sqrt{\left(1 - \frac{R_P}{R_*}\right)^2 - \left(\frac{a_P}{R_*} \cos \iota\right)^2} \quad (24)$$

Analogously, for the total transit duration  $t_T$ , we find

$$t_T = \frac{P}{\pi a_P} \sqrt{(R_* + R_P)^2 - (a_P \cos \iota)^2} = \frac{PR_*}{\pi a_P} \sqrt{\left(1 + \frac{R_P}{R_*}\right)^2 - \left(\frac{a_P}{R_*} \cos \iota\right)^2} \quad (25)$$

We know from (20) that  $R_P/R_* = \sqrt{\Delta F}$ . By subtracting  $t_F^2$  from  $t_T^2$ , we eliminate the term involving the inclination  $\iota$ . The remaining expression can be rearranged to solve for  $a_P/R_*$ , yielding

$$\frac{a_P}{R_*} = \frac{2P}{\pi} \frac{\Delta F^{1/4}}{\sqrt{t_T^2 - t_F^2}}. \quad (26)$$

The right-hand side now contains only observable quantities. The stellar radius  $R_*$  is obtained from the star's spectrum and stellar models. For transiting planets, we can thus determine the orbital radius  $a_P$  (or, for more complex analysis of elliptical orbits: the semi-major axis).

Without relying on stellar models, we can directly obtain the star's average density from the above formulas. For  $M_* \gg M_P$ , which holds in such systems, equation (10) simplifies to

$$a_P^3 = \frac{GM_*}{4\pi^2} P^2. \quad (27)$$

Substituting  $a_P$  from (26) into this equation gives the average stellar density:

$$\rho_* \equiv \frac{M_*}{\frac{4}{3}\pi R_*^3} = \frac{24P}{G\pi^2} \frac{\Delta F^{3/4}}{(t_T^2 - t_F^2)^{3/2}}. \quad (28)$$

The right-hand side contains only observable quantities—the average density of the star can thus be determined directly from observations!