Planets & Exoplanets PH20104

EXOPLANETS

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Revision of basics facts about stars

1. Stars often described in terms of solar properties $M_\odot = 2 \times 10^{30}\,\mathrm{kg}$, $R_\odot = 6.96 \times 10_8\,\mathrm{m}$
2. Stellar masses range: $\approx 0.5 M_\odot$ to $\approx 200 M_\odot$
3. $M_* \sim T_{*\mathrm{eff}}$ We measure $T_{*\mathrm{eff}}$ by spectroscopy, so we know M_*
4. $M_* \sim R_*$ So we also know R_*
5. Stars spin around an axis with speeds from $V_{*\mathrm{rot}} \approx 10$ to $200\,\mathrm{km\,s^{-1}}$
6. $V_{*\mathrm{rot}} \sim M_*$
7. Stellar surfaces are not uniform brightness - ‘star spots’.

Revision of basics physics

Kepler’s third law $\dfrac{a^3}{p^2} = \dfrac{G\left(M_* + Mp\right)}{4\pi^2}$ where, in most cases $M_* \gg M_p$ so $M_* + M_p \approx M_*$ so

Selection effects

Hard selection effects

We can not detect (or infer the existence or absence of objects outside the capabilities of our instrumentation)

Soft selection effects

Some objects may, in principle, be detectable but may be rare, and their environment may swamp the signal. Once we have made some detections of these object, we can use a statistical argument to infer the true size of the population from the apparent size of the population observed. This is called a completeness correction.

Detecting exoplanets

The three main types of exoplanet detection mechanism

1. Light reflected by the surface of the planet - **Direct imaging**.
2. Light being blocked by the planet as it passes in front of the star - **Transit**.
3. A change in the spectrum of the star's light as it moves under the gravitational influence of the planet - **Radial velocity**.

Other methods

1. Long term repeated patterns of apparent movement (tangential) of stars in a series of images - **Astrometry**.
2. Repeated short periods of brightening of stars in series of images due to relativistic effects - **Microlensing**.
3. Repeated incidents of polarisation of a star's light as that light passes through a planetary atmosphere - **Polarimetry.**
4. Anomalies in the orbital timings of previously discovered planets that may be caused by as-yet undetected planets - **Timing variations**.

Direct Imaging

$$\theta = \sin\left(\frac{a}{d}\right) \approx \frac{a}{d}$$

θ is the angular separation on the sky between the planet at its parent star (in rad).
a is the semi-major axis of the planet's orbit
d is the distance from the star to us.

$$\frac{L_p}{L_*} = A\frac{R_p^2}{4a^2} \qquad \frac{L_P}{L_*} < 10^{-6}$$

L_p is the 'luminosity' of the planet.
L_* is the luminosity of the star.
A is the Bond albedo of the planet - the fraction of light from the star that is reflected back into space. A is a dimensionless number between 0 and 1.
R_p is the radius of the planet.

As of 24th March 2023 the NASA exoplanet archive lists 64 exoplanets that were discovered by direct imaging.

Direct Imaging - Pros and Cons

Unable to constrain mass of planet.
Most sensitive to planets with large R_p, high A, large a. (Super Jupiter type planets)

Requires multiple observations over long periods of time for confirmation. Risk of confusion with background stars.

Possibility of doing spectroscopy on planetary atmospheres to measure temperature of planet, or even atmospheric composition.

The transit method.

If a planet passes in front of its star (LoS) we can measure:-

- The orbital period of the planet.
- The radius of the planet.
- The semi major axis of the orbit.

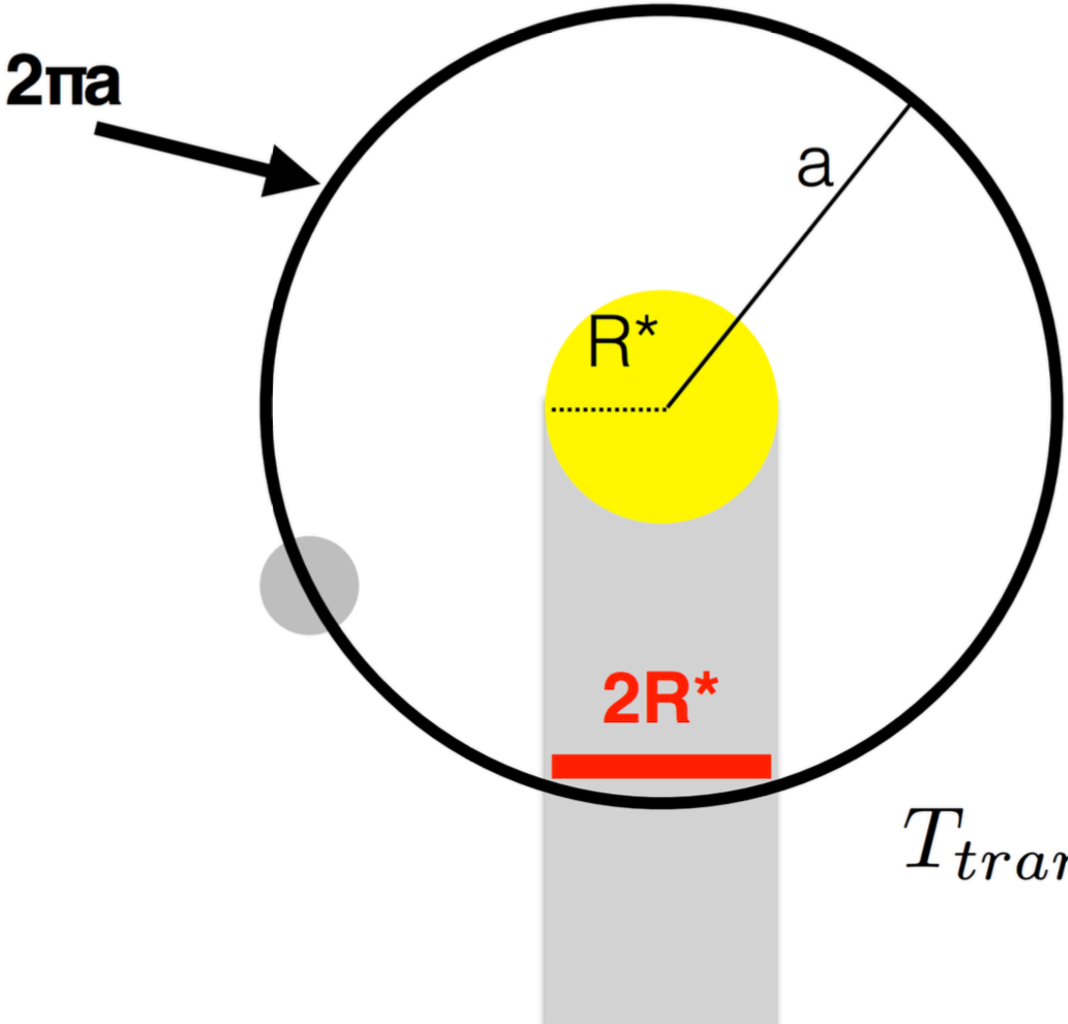
$$a \approx \left(GM_* \left(\frac{P}{2\pi} \right)^2 \right)^{\frac{1}{3}}$$

$$\frac{\Delta F}{F} = \frac{R_p^2}{R_*^2}$$

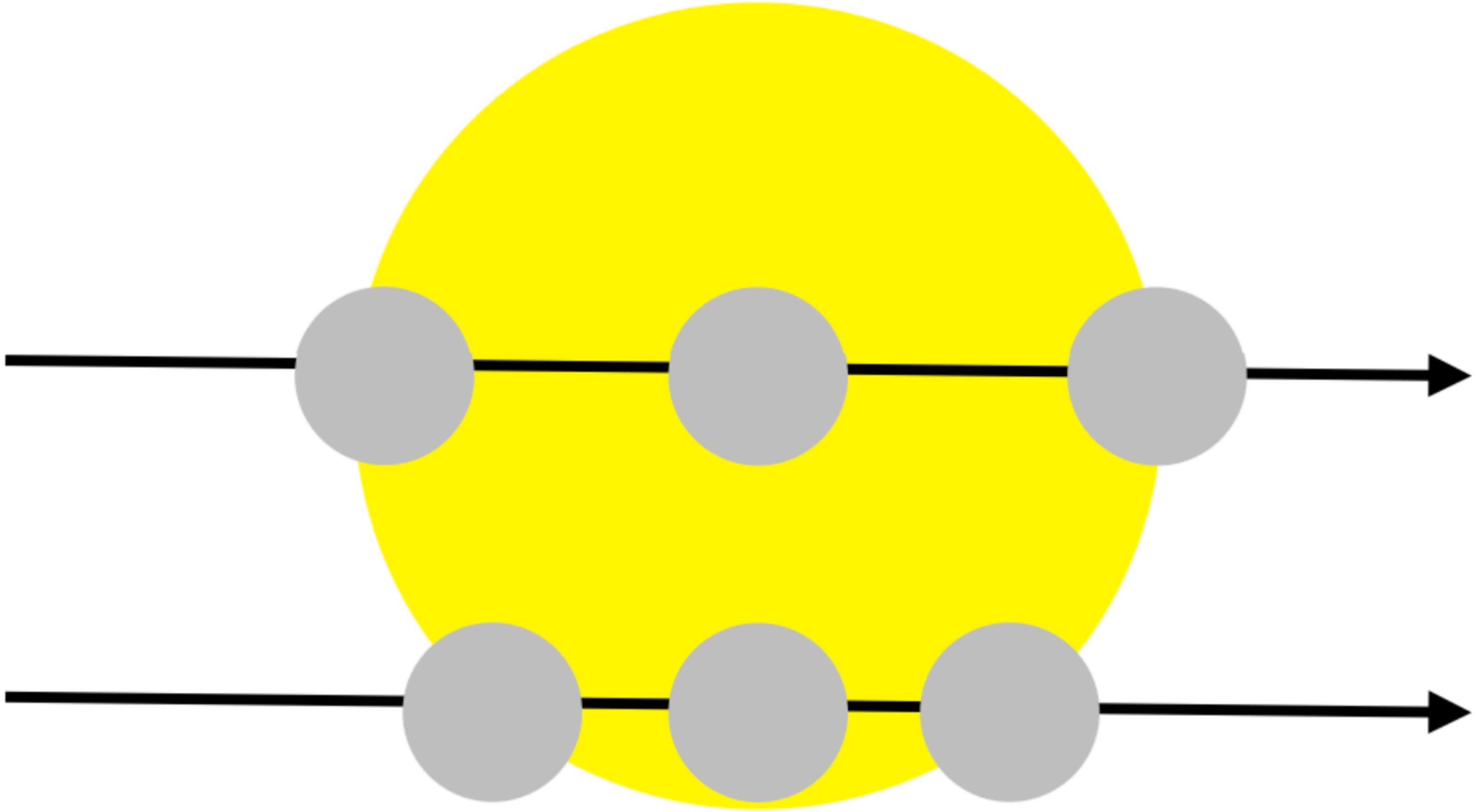
$\frac{\Delta F}{F}$ is the fractional reduction in the flux received during the star in the middle of the transit.

$$T_{trans} = P \frac{R_*}{\pi a}$$

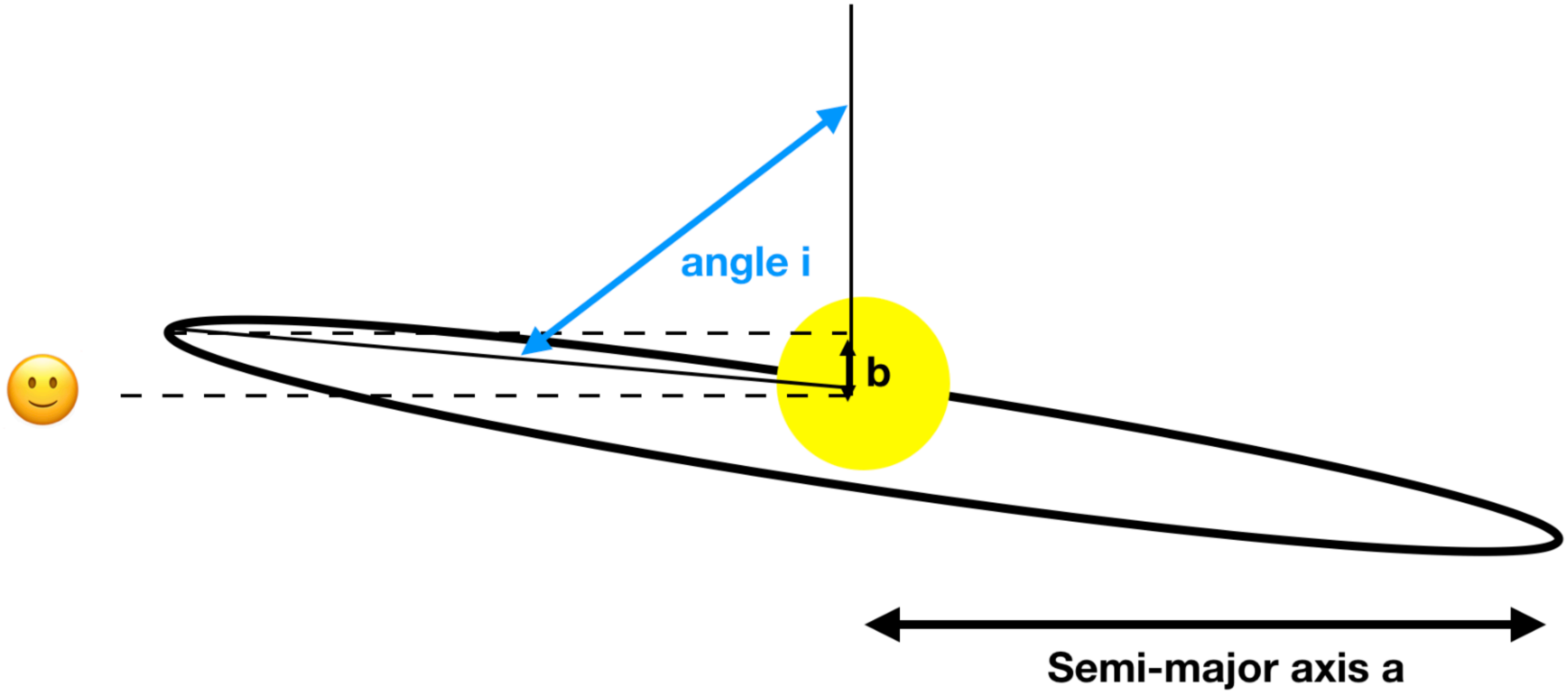
T_{trans} is the duration of the transit.



$$T_{transit} = P \times \frac{R*}{\pi a}$$



Sketch to show the effect of impact parameter on transit duration



Sketch showing impact parameter b and orbital inclination angle i along with the semi-major axis of orbit a.

$$b = a \cos i$$

We can detect transits only when

$$a \cos i \le R_* + Rp$$

For systems where

$$R_* - R_p < a \cos i \le R_* + R_p$$

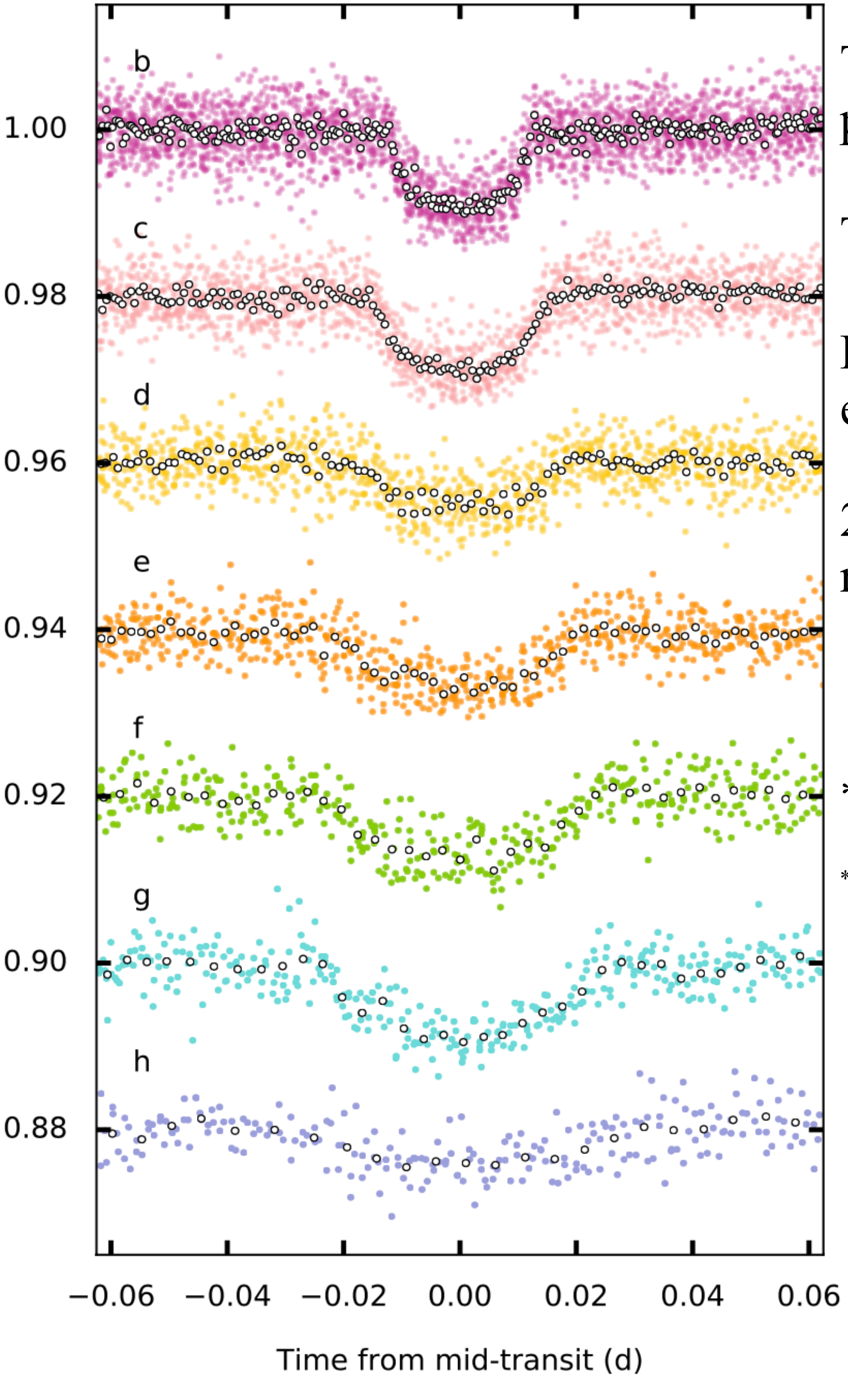
The the planet's orbit, as viewed from our position, just grazes the edge of the star.

In this case we detect a shallower and narrower dip that we would see for a planet that transits across the middle of the stellar disk.

Assuming that orbital planes are randomly distributed $\left(0^o \le i \le 90^o\right)$, the probability of a planet being observed as a transit is

$$\text{Prob} = \frac{\#\,\text{transiting orbits}}{\#\,\text{all possible orbits}}$$

An example of a transiting system.



Trappist*-1 system was discovered in 2016. Two earth sized planets were found first, and five more in 2017.

The parent star has a mass of $\sim 9 \times 10^{-2} M_{\odot}$.

Planets d, e, f, & g are in the *Goldilocks* zone - so lots of excitement about possible life.

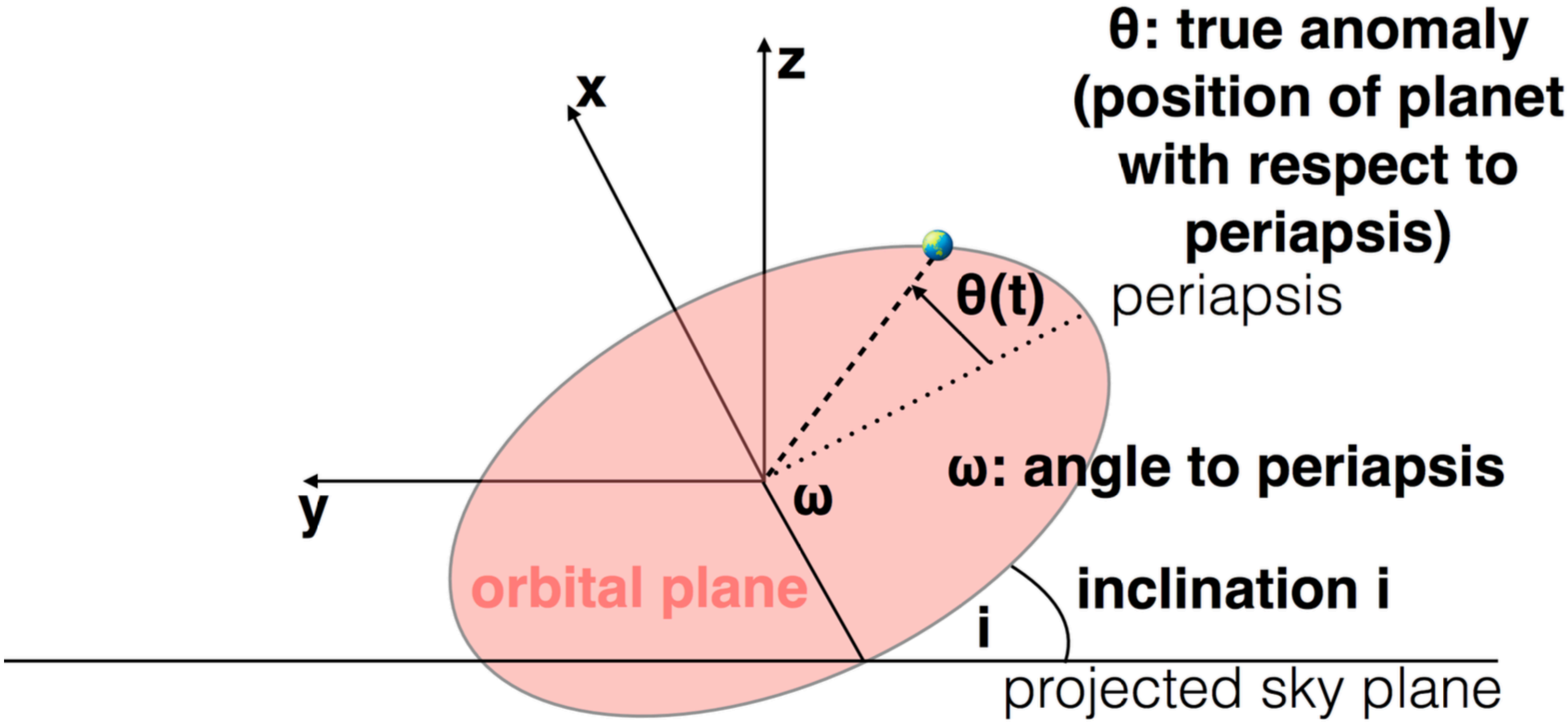
27th March 2023 - JWST** releases planetary atmosphere result for Trappist-1b - no atmosphere.

*Trappist = ‘**T**ransiting **p**lanets and **p**lanetes**i**mals **s**mall **t**elescope

** https://www.esa.int/Science_Exploration/Space_Science/Webb/Webb_measures_the_temperature_of_a_rocky_exoplanet

Grimm, S. L., Demory, B-O., Gillon, M., et al. May 2018 *A&A* **613** A68. arXiv:1802.01377

The radial velocity method



Sketch showing the radial velocity method of detecting exoplanets

This is a gravitational method

A star and its planet orbit around their common centre of mass.

We can use spectroscopy to detect the ‘Doppler wobble’ as the star moves back and forth

Typical velocities are of the order of $\mathrm{m\,s^{-1}}$ i.e. human walking speed

We will derive the equations of motion for the planet in cartesian coordinates first.

ω = angle of periapsis (the point at which the planet is closest to the star) *wrt* line of sight.

θ = position angle of planet *wrt* periapsis.

The velocities in the x, y, & z directions are v_x v_y & v_z.

$$v_x = -\frac{2\pi a}{P\sqrt{1-e^2}}\left(\sin(\theta+\omega) + e\sin(\omega)\right)$$

$$v_y = -\frac{\cos i \, 2\pi a}{P\sqrt{1-e^2}}\left(\cos(\theta+\omega) + e\cos(\omega)\right)$$

$$v_z = -\frac{\sin i \, 2\pi a}{P\sqrt{1-e^2}}\left(\cos(\theta+\omega) + e\cos(\omega)\right)$$

i = inclination angle, a = semi-major axis, e = eccentricity, ω and θ as defined above.

We now have the planetary motion in the *astrocentric* (*wrt* star) frame, $\overrightarrow{v_{p,*}}$.

$$\overrightarrow{v_{p,*}} = \overrightarrow{v_p} - \overrightarrow{v_*}$$

where $\overrightarrow{v_p}$ is the velocity of the planet *wrt* the barycentre of the system.