Expanded Ground-Based Kepler Array: Phase 2

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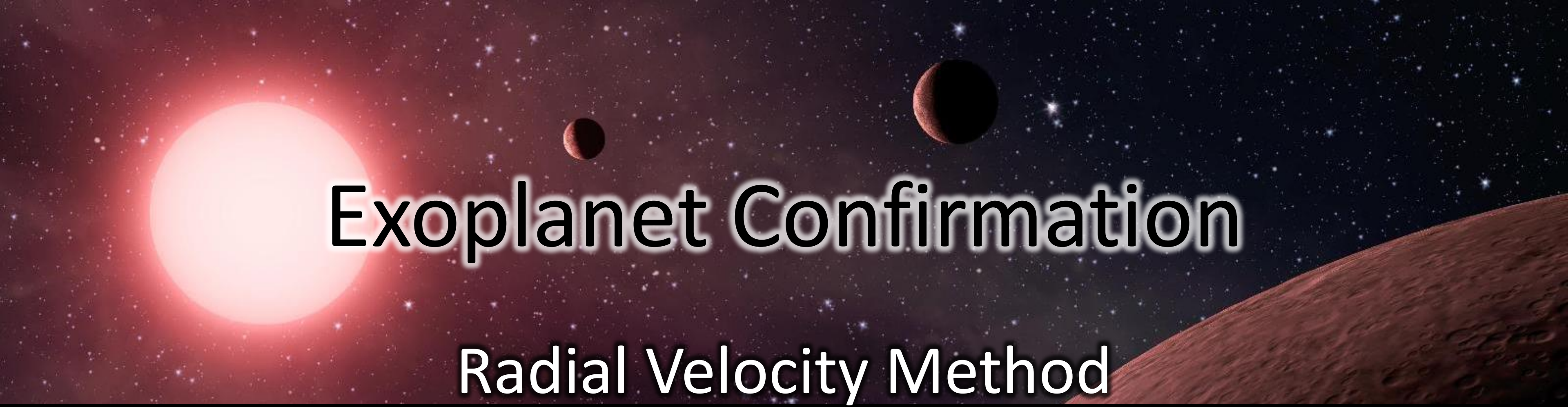
Mission Objective

- Multi-phase approach
  - Phase I: Detection
  - Phase II: Confirmation and Characterization
- Radial velocity confirmation
- Mass determination
- Atmospheric spectroscopic analysis



Exoplanet Confirmation

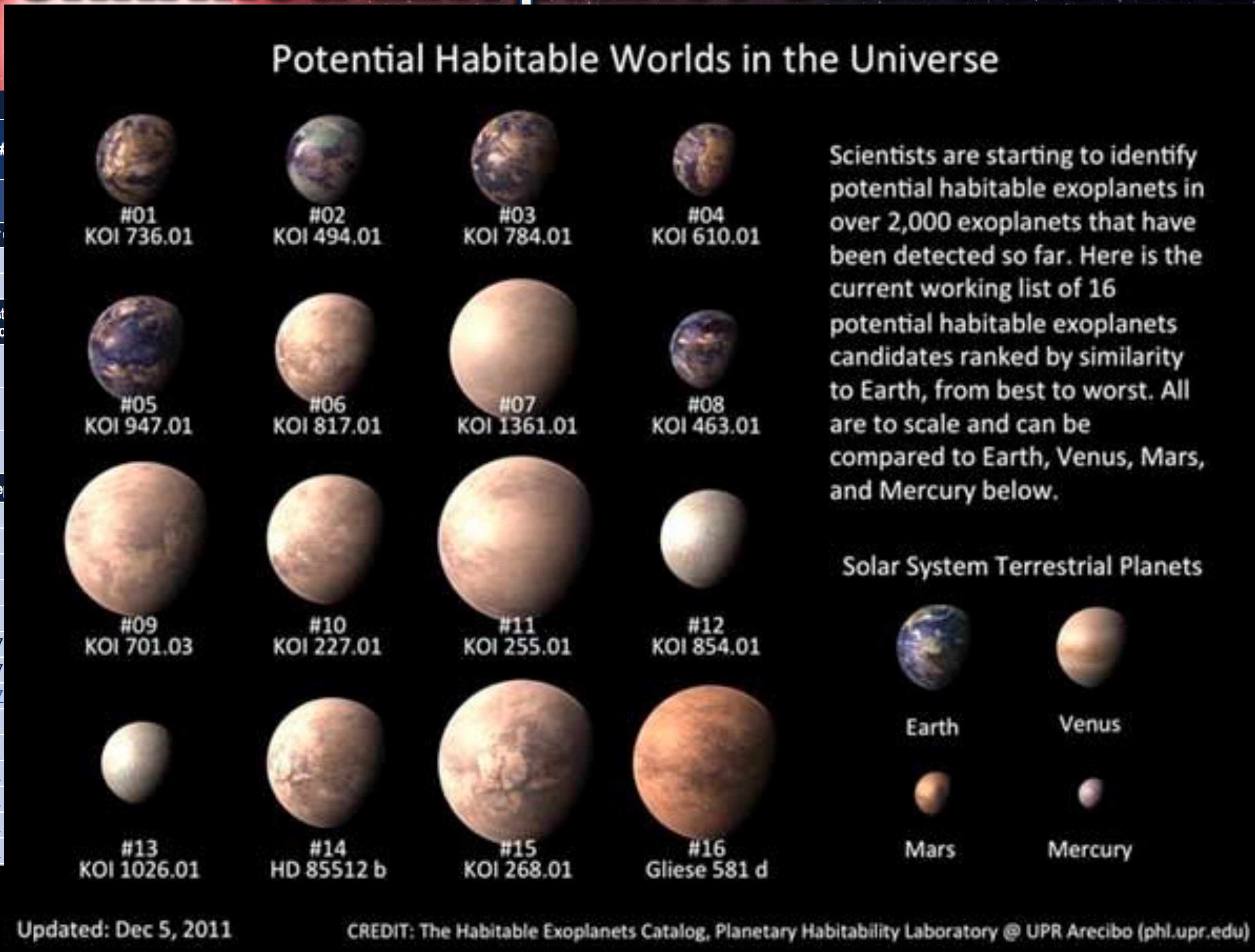
Radial Velocity Method

Kepler and Other Exoplanet Statistics

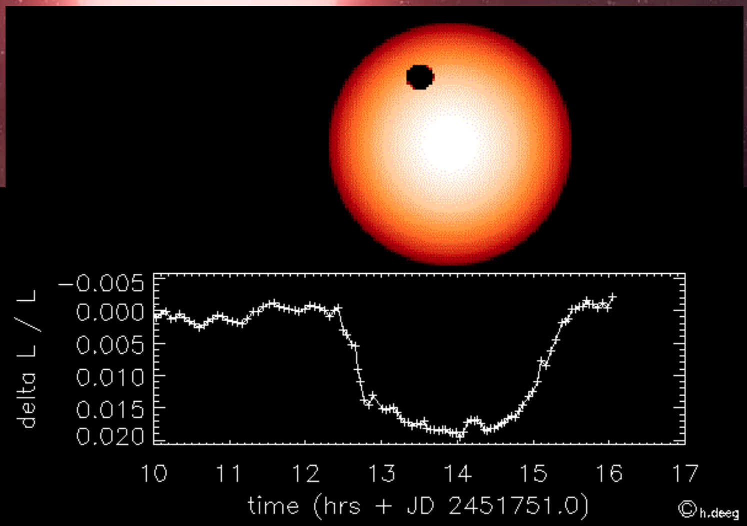
- Kepler has identified **2,740** potential planets orbiting 2,036 stars
- *Only* 114 confirmed earth-like exoplanets
- Kepler Input Catalog
  - The Kepler SCP targets were observed by the 2MASS project as well as Sloan filters
  - The catalog is not used for finding Kepler targets because only a portion can be observed by the spacecraft.
  - The full catalog includes up to 21 magnitude, giving 13.2 million targets, but of these only about 4.5 to 6.5 million are in Kepler's FOV
  - Other programs can look at these extra targets in Kepler's FOV, as well as other sky coverage

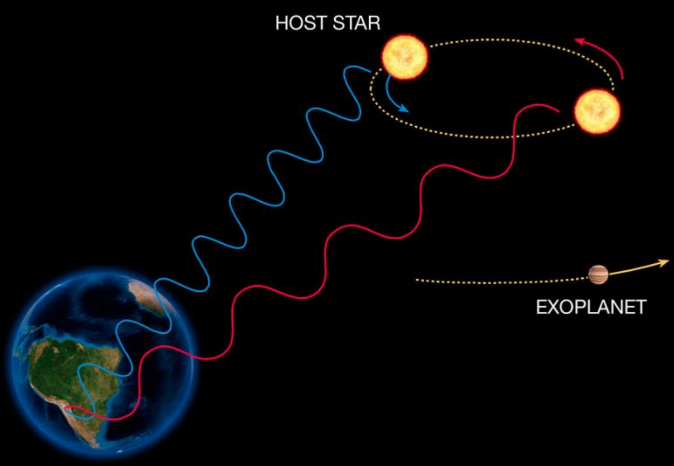
Confirmed Exoplanet Characteristics

Name	KOI #	on	Kp	Last Updated
		ss	*Mag*	
Earth and Jupiter for				
Earth				
Jupiter				
The first 3 planets list They are listed to allo				
TrES-2 Kepler 1b		59	11.3	2010/01/04
HAT-P-7b Kepler 2b		10	10.5	2010/01/17
HAT-P-11b Kepler 3b		51	9.2	2010/01/04
Kepler team and Ke				
Kepler-4b	7	09	12.2	2010/01/17
Kepler-5b	18	06	13.4	2010/01/17
Kepler-6b	17	24	13.3	2010/01/17
Kepler-7b	97	23	12.9	2010/01/17
Kepler-8b	10	04	13.6	2010/01/17
Kepler-9b	377	.2	13.308	2010/12/01
Kepler-9c	377	.2	13.308	2010/12/01
Kepler-9d	377	.2	13.308	2010/12/01
Kepler-10b	72	8.7	10.96	2011/01/10
Kepler-10c	72	8.7	10.96	2011/05/23
Kepler-11b	157	2.9	13.7	2011/02/02
Kepler-11c	157	2.9	13.7	2011/02/02
Kepler-11d	157	2.9	13.7	2011/02/02
Kepler-11e	157	2.9	13.7	2011/02/02



Confirming Potential Candidates





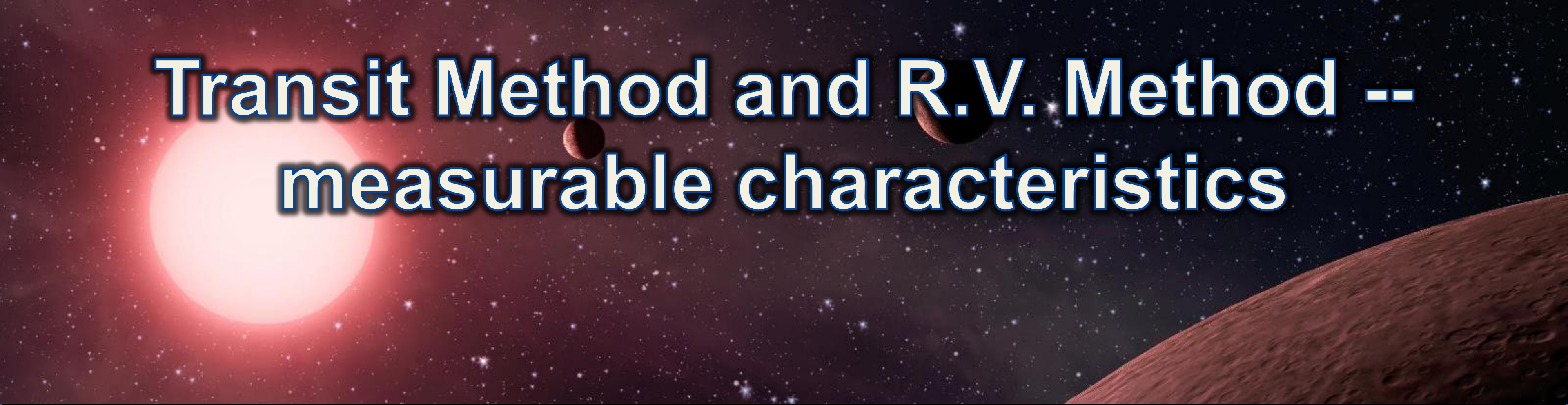
Methods of Confirmation

1. Transit Method

   For this project, this method was used to locate targets to confirm. Based on the star's mass, and planet's orbital period observed many candidates can be thrown out as they are out of the habitable range.

2. Radial Velocity Method

   For this project, this will be the method used for confirming the targets located by other programs



Transit Method and R.V. Method -- measurable characteristics

- With the Transit Method used in Phase One of the project, we are able to measure the planet’s period, semi-major axis, inclination, and radius.
- With the Radial Velocity method, we are able to find the period, semi-major axis, eccentricity, and upper/lower limits for the planet’s mass. This step rules out most false positives, further confirmation requires direct imaging of the star during the planet’s transit.

Radial Velocity – The Stellar Wobble

- As a planet orbits its star, gravitational effects pull the center of mass of the system out of the center of the star
- This leads to the star having a measurable orbit around this center of mass
- With star orbiting the CoM, Doppler Shifts can be seen in the spectral lines
- These shifts depend on the inclination of the star system to Earth, and the position of the star in its orbit

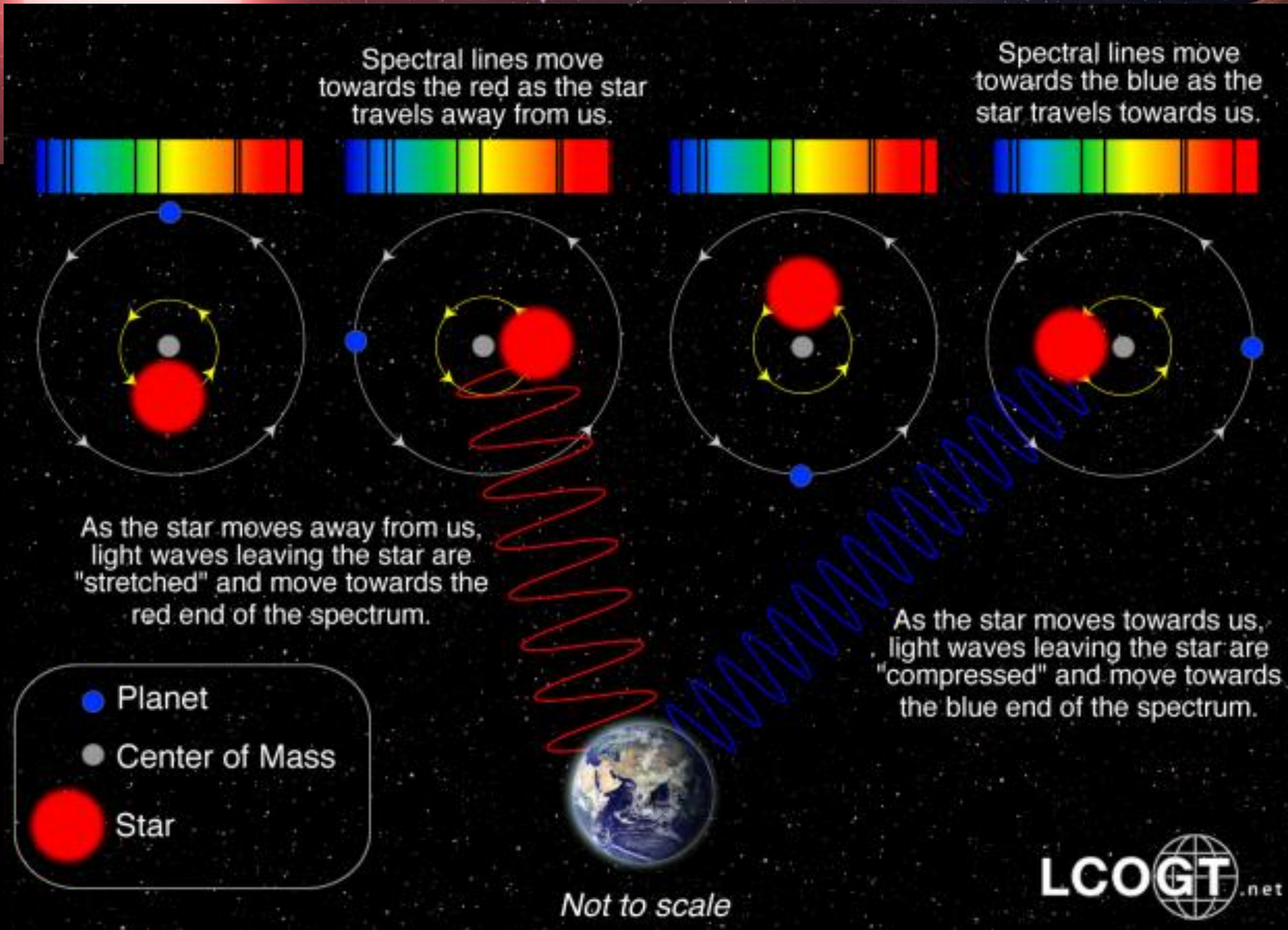
Measuring the Doppler Shift

- Spectroscopy
  - typical requirements for radial velocity measurement
    - High-Res spectrograph: 1 m/s velocity variations
    - Over the visible spectrum
    - Needs to keep Velocity noise less than 2 m/s
- Radial Velocity requires a component of motion directly pointed toward Earth
- As the star moves directly toward Earth, the spectral lines are blueshifted
- As the star moves directly away from Earth, the spectral lines are redshifted
-
- $$\lambda = \frac{c}{v}$$

As the star moves away from observation point, v decreases →increases observed wavelength

Likewise, as the star moves toward the observer, v increases →decreases observed wavelength

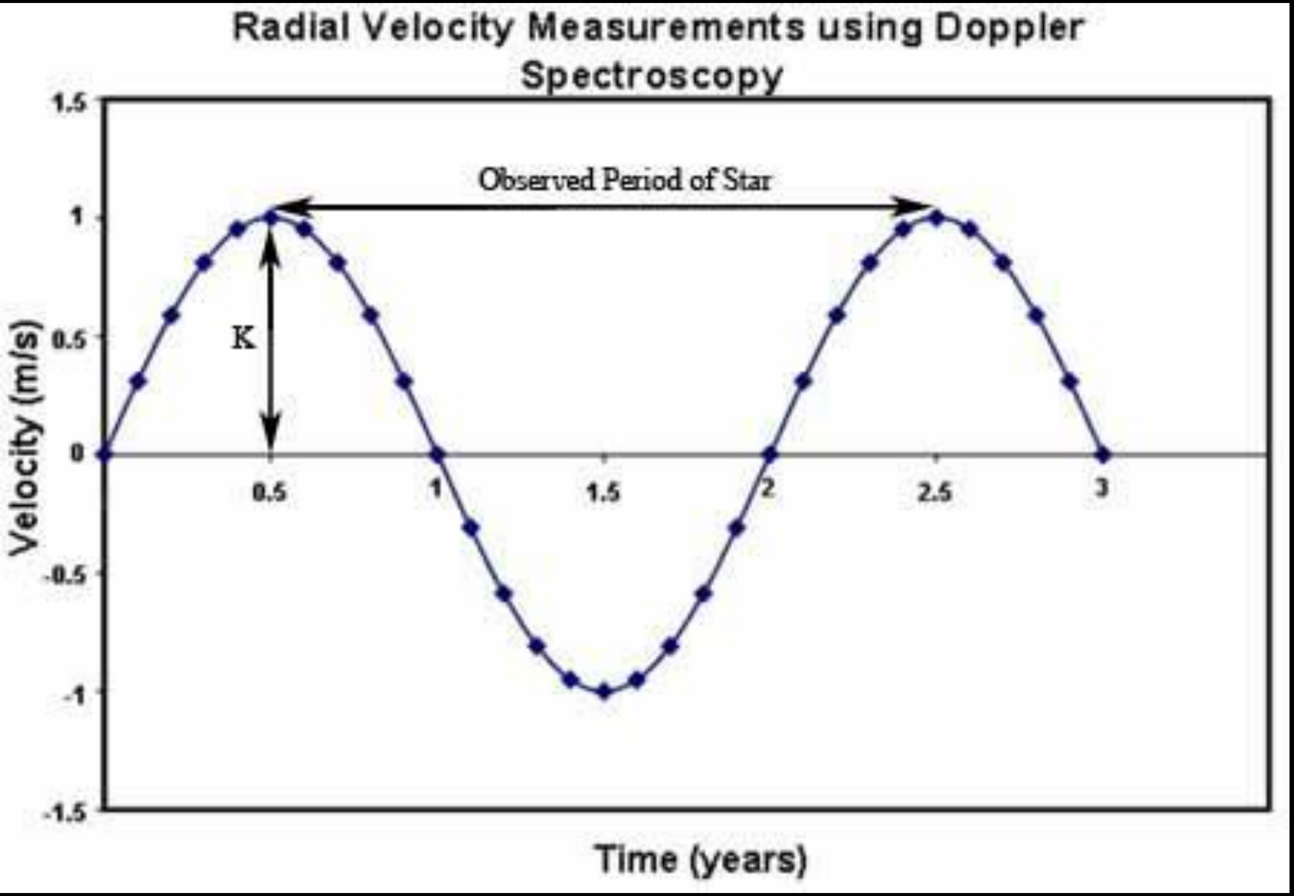
Pictorial Representation of the Radial Velocity Method



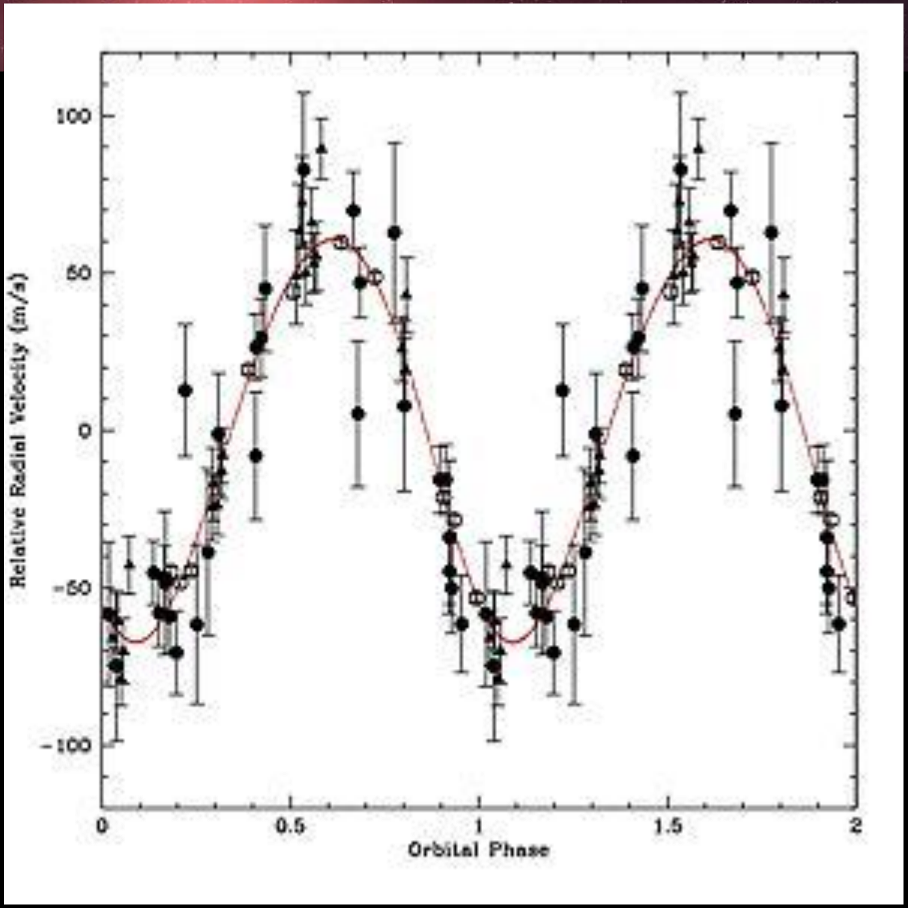
Radial Velocity Procedure

- Take spectrum of candidate star
  - use stellar spectrum to estimate stellar mass
- Continue to take spectra over predicted orbital period from transit method
- Calculate the radial velocity from the shift of the spectral lines in each spectra as a function of time
- Plot the radial velocity vs. orbital time or orbital phase
- With this plot, bounds for the mass of the planet can be determined
- Examples of these plots can be seen below

Theoretical Measurements of Radial Velocity vs. Time using Doppler Spectroscopy



Actual Measurements of Radial Velocity vs. Orbital Phase using Doppler Spectroscopy



As seen here, the measured radial velocities have large error bars associated with them because of the precise nature needed when measuring, and uncertainty in the angle of incidence to Earth. The periodic function (shown in red) is a best fit curve of the measured data

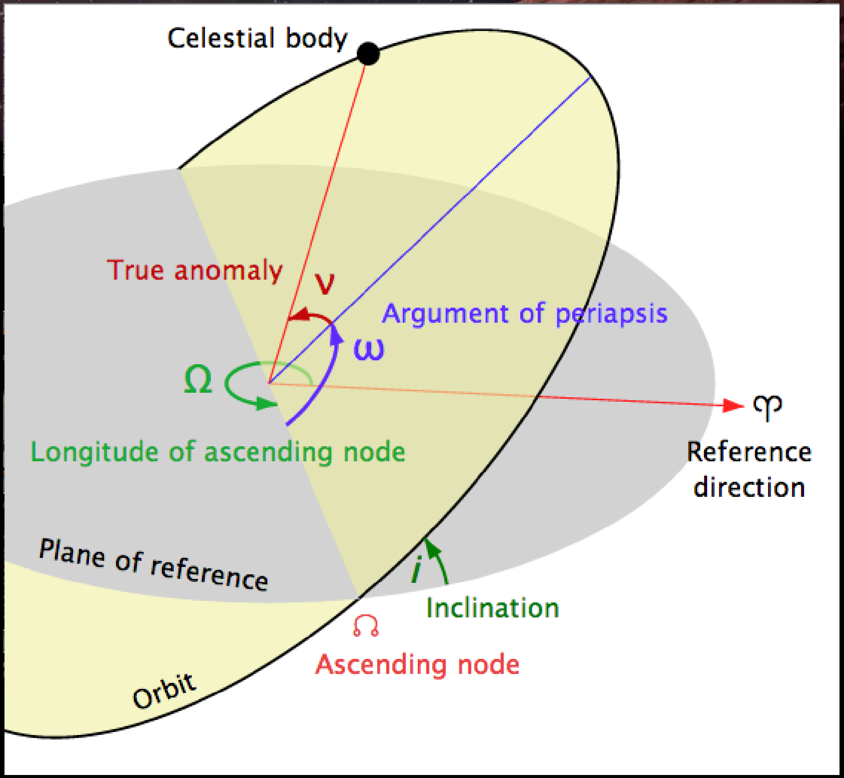
Radial Velocity Signal

$$K = \left(\frac{2\pi G}{P_{\text{orb}}}\right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

- The method gives us the radial velocity, eccentricity, and confirms orbital period seen from transit method.
- Without direct imaging it is difficult to determine the angle of inclination, *i*.
- We can assume upper and lower bounds of that angle to set bounds for the mass of our planet.

More on Orbital Angle of Inclination

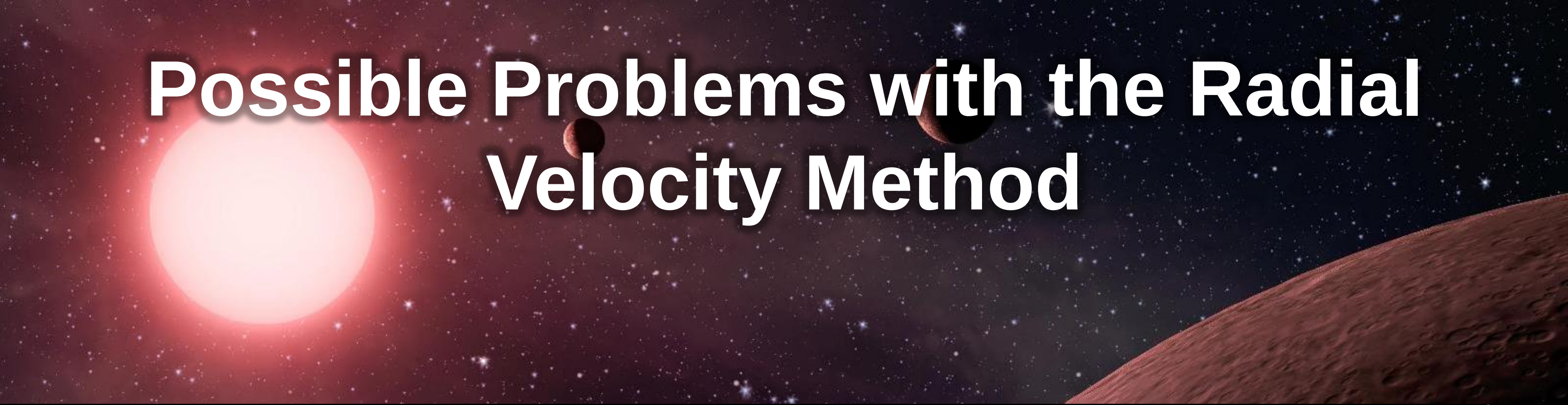
- i=0º - Orbit is parralel to sky; unobservable.
- i=90º - Orbit is perpindicular to sky. A.K.A. the planet passes through the 'middle' of the star.
- Generally, we observe planets in the range of **45º < i < 135º**. We can use these numbers to set bounds for our planet mass



$$K = \left(\frac{2\pi G}{P_{\rm orb}}\right)^{\frac{1}{3}} \frac{M_P \sin i}{(M_* + M_P)^{\frac{2}{3}}} \frac{1}{\sqrt{1-e^2}}$$

Simulation

Possible Problems with the Radial Velocity Method



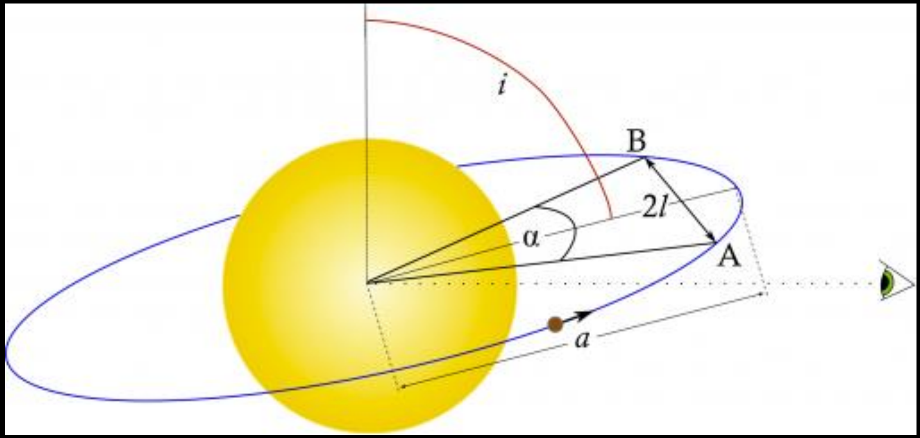
- Only sun-like stars or cooler are candidates for the method because hot stars (of classes O, B, and A) do not have enough narrow spectral lines
- Some systems do not have planets that have observable/calculable angle i, but this does not affect us as for a transit to occur, the planet must already be within the observable range of orbital inclination
- The Earth's rotation and revolution must be corrected for
- Stellar properties such as rotation, spots, and convection can affect the Doppler Shift
- Due to Kepler's Third Law, there is some detection limit of radial velocity of stars. This detection limit is proportional to the square root of the amplitude of the signal
- Earth-like planets around Sun-like stars induce a velocity of only ~9 cm/s, making them difficult to detect However, this helps narrow down candidates when the velocity is too large or too small.

Measuring exoplanet mass exactly

- We only measure the component of the star’s velocity that points in the direction of Earth.
- If a planet has inclination *i* of exactly 90° then we will measure the true radial velocity and get the true mass.
- Otherwise, we can only find a lower bound on the planet’s mass.

Radial velocity equation (ignoring eccentricity)

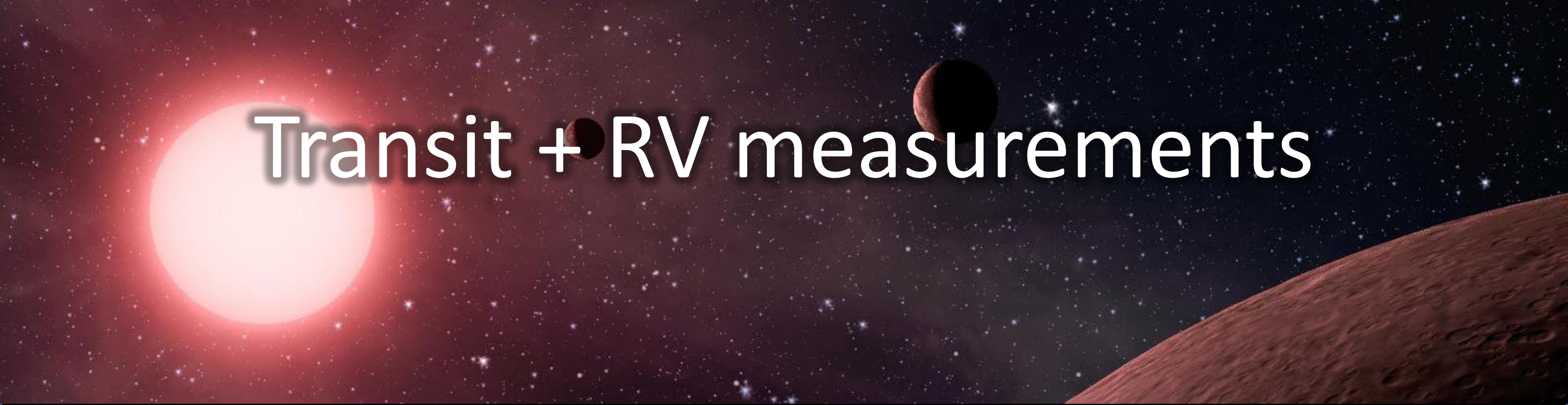
$$K \approx \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} M_s^{-\frac{2}{3}} M_p \sin i$$



- Lower bound on mass when sin(i)=1

$$M_{\min} = K\left(\frac{2\pi G}{P}\right)^{-\frac{1}{3}} M_s^{\frac{2}{3}}$$

Transit + RV measurements



- If we are measuring the mass of a planet for which we have already observed a transit, we can find an upper bound for the mass

$$[\sin i]_{\min} = \sqrt{1 - \left(\frac{R_s + R_p}{r} \right)^2}$$

$$M_{\max} = K \left(\frac{2\pi G}{P} \right)^{-\frac{1}{3}} M_s^{\frac{2}{3}} \left(1 - \left(\frac{R_s + R_p}{r} \right)^2 \right)^{-\frac{1}{2}}$$

Using transit measurements to solve for the inclination angle

- If the inclination is exactly 90°, then:
  - Planet will pass through center of star
  - Distance traveled during transit is $2*(R_s+R_p)$

- If the inclination is not exactly 90°, then:
  - Planet will not pass through center of star
  - Distance traveled during transit is $2*[(R_s+R_p)^2 - r^2\cos^2(i)]^{1/2}$

- This lets us find an angle α such that $\alpha/2\pi$ is the fraction of the orbital period P traveled in the transit duration T, ie:

$$T = P\frac{\alpha}{2\pi} = \frac{P}{\pi}\arcsin\left(\frac{\sqrt{\left(R_s + R_p\right)^2 - r^2\cos^2 i}}{r}\right)$$

- We can solve for sin(i):

$$\sin i = \sqrt{1 - \sin^2\left(\frac{T\pi}{P}\right) - \left(\frac{R_s + R_p}{r}\right)^2}$$

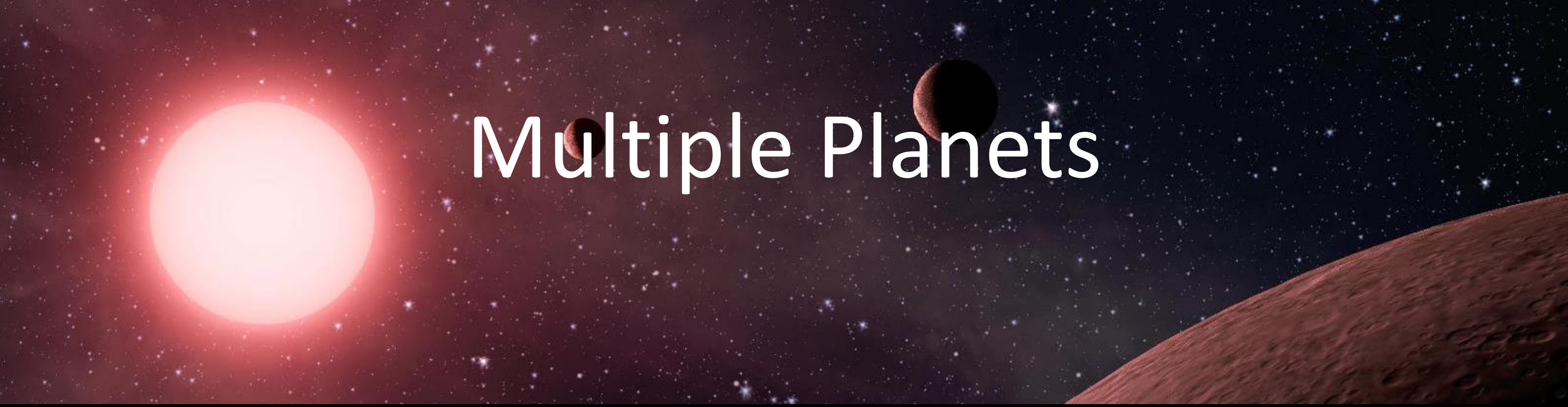
- Which gives us the true mass of the planet:

$$M_{true} = K\left(\frac{2\pi G}{P}\right)^{-\frac{1}{3}} M_s^{\frac{2}{3}}\left(1 + \sin^2\left(\frac{T\pi}{P}\right) - \left(\frac{R_s + R_p}{r}\right)^2\right)^{-\frac{1}{2}}$$

Multiple Planets

- For multiple planets transiting a star:
  - T<<P
  - Look for long enough and you should be able to pick out the transit events corresponding to each planet
- Radial velocity might be harder:
  - All of the planets are constantly affecting the star’s movement
  - Hard to model if you don’t know anything about the planets

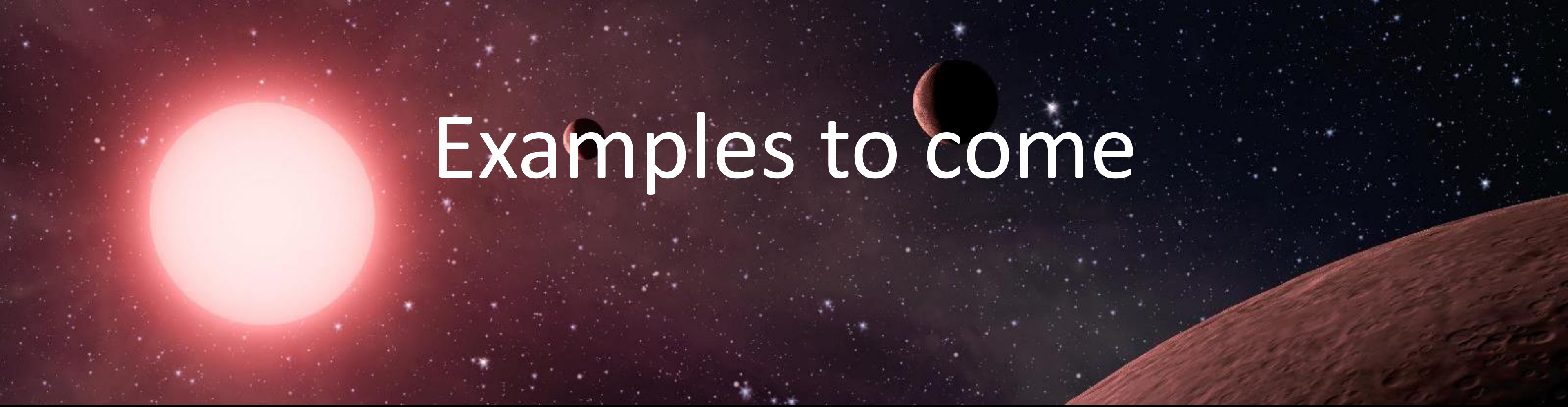
Multiple Planets



- Recording transits and RV data simultaneously might make the problem easier
- Example:
  - Two planets orbit a star along the same path with an orbital period of 1 year, but are separated by 6 months.
  - This would give us problems with both transit and RV methods

Finding the mass of a non-transiting planet

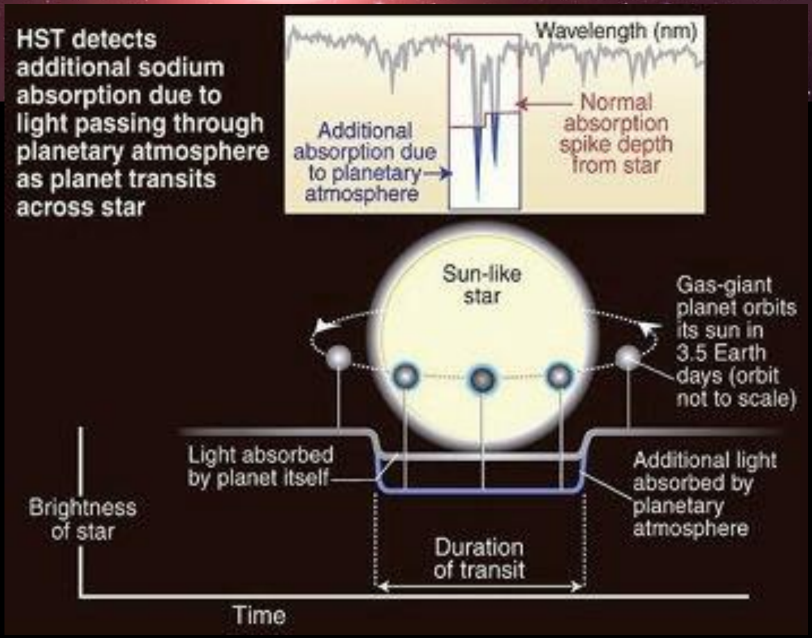
- RV can only find $m_{p,min}=m_p \sin i$ *where* m_p is the unknown planet mass because the RV of the planet is not measured directly and so neither is *i*
  - *i* can be found through transit and so exact mass can be found
    - *However, most extrasolar planets are non-transiting*
    - *Ones with the largest min masses are considered "planetary candidates" due to the posibility of them being brown dwarfs*
- Exact mass can be found by RV signal via high-resolution $\left(R = \frac{\lambda}{\Delta\lambda} > 40{,}000\right)$ using spectroscopy with very large telescopes
  - Key: observe large number of spectral features coming from the planet and observe at different orbital phases in that the traveling faint planetary signal can be disentangled from the dominating stellar one
    - *Carbon Monoxide (CO) detection is key due to "dense forest" of deep absorption lines in spectral band around 2.3μ*
      - CO is one of the most abundant molecules in hot gas giants exoplanets
      - τ Boo b has been confired as a m_p=5.6$\pm$ 0.7M_{Jup} (Rodler et. al 2012) using ECO Telescopes at the Paranal Observatory



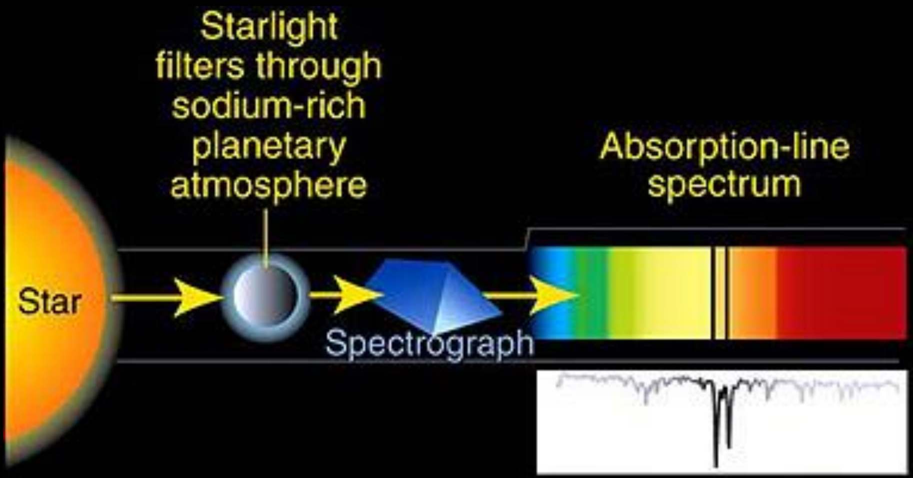
Examples to come

- Currently the stars with earth-like planets found by Kepler are too faint to do these calculations of to find the mass from the ground
  - But with *ESPRESSO* (Echelle Spectrograph for Rocky Exoplanets and Stable Spectrscopic Observations) to be installed at Paranal ESO's VLT
  - NGTS to be located at ESO Paranal observatory will be able to detect Neptune and Super-Earth mass planets

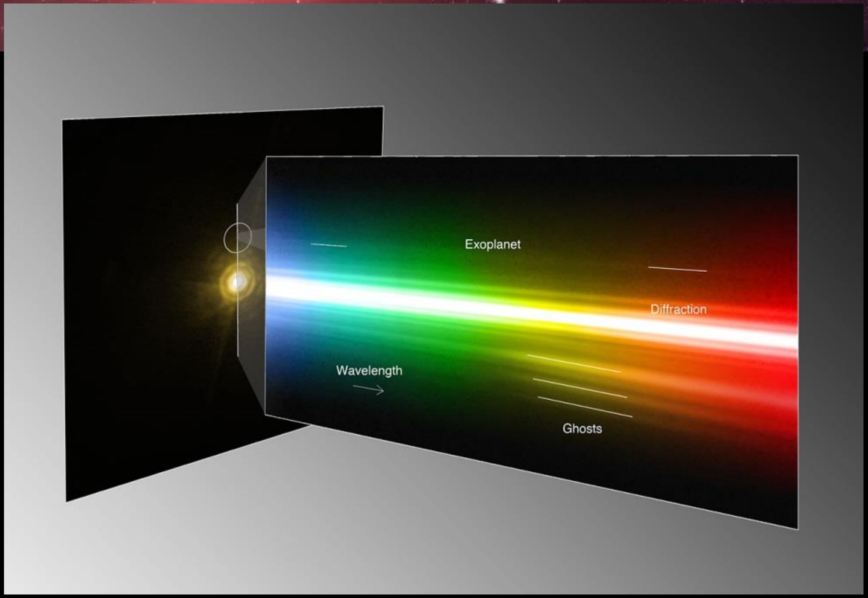
Atmospheric Composition: Spectroscopy



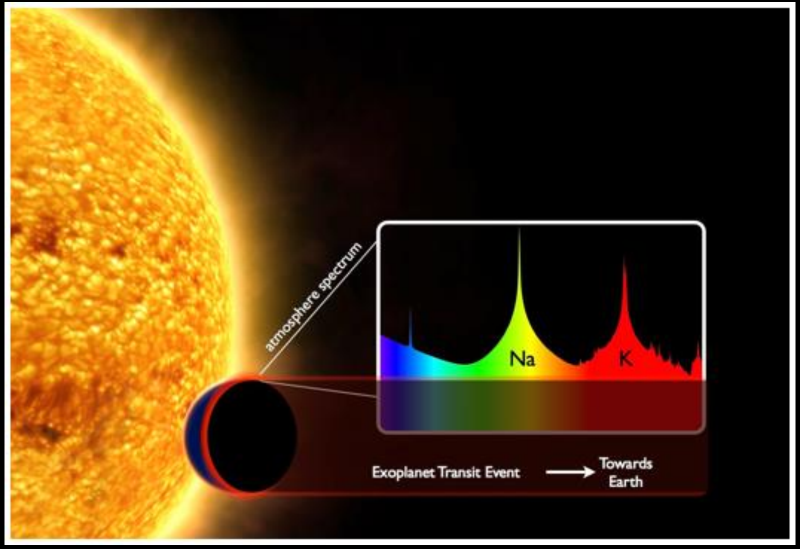
- Spectroscopy uses dispersion and diffraction to determine molecular composition of a sample by absorption and refractive index as a function of wavelength.
- Separates light through a spectrograph into a spectrum.
- A spectrum of the transmitted light shows absorption lines used to identify composition.
- Our sample is the atmosphere of the transiting planet.



Atmospheric Composition: Exoplanet Spectroscopy



- Interest in nearby Earth-like planets orbiting a star
- Atmospheres composed of gases that are necessary for or caused by life(O_2, O_3, CO_2, CH_4 and H_2O).
- During a transit across a star, the light of the star travels through the atmosphere of the planet and causes dispersion affecting the spectrum.

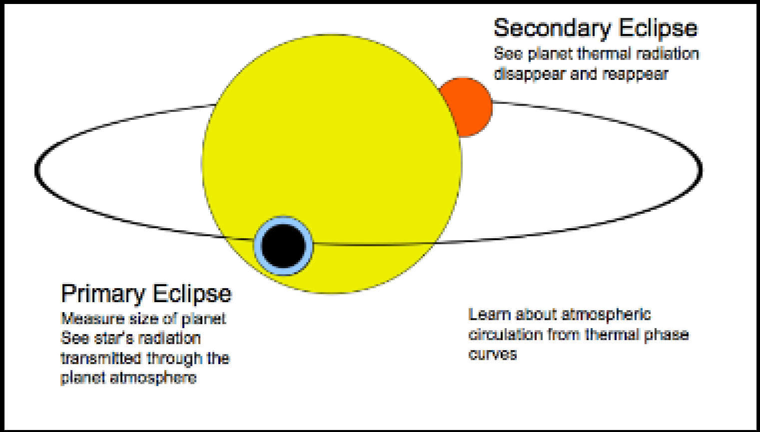


Atmospheric Composition: Spectroscopy

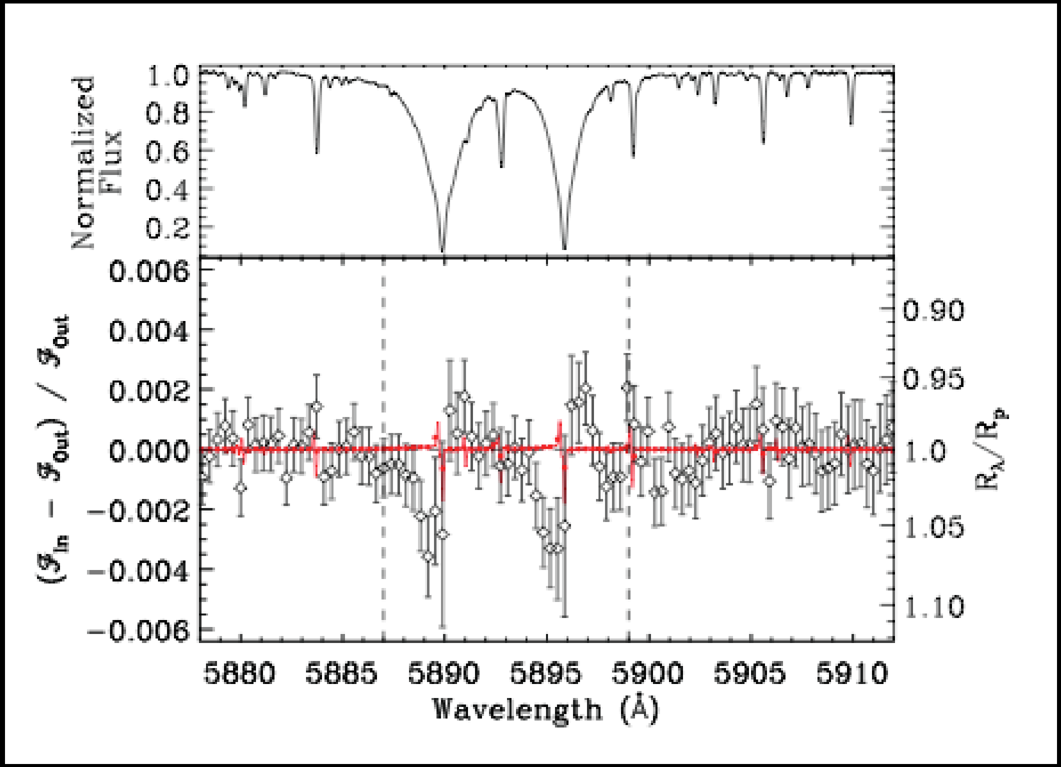
- A planetary transmission spectrum = (spectrum of the star and planet during transit) / (spectrum of the star at occulation)

- Total flux of spectrum would be obtained from subtracting (Planet+star spectrum) – Star Spectrum,

- Planetery Flux and transmission gives :
  - Atmospheric composition
  - Temperature gradient (IR)
  - Albedo (visible)



Atmospheric Composition: Spectroscopy

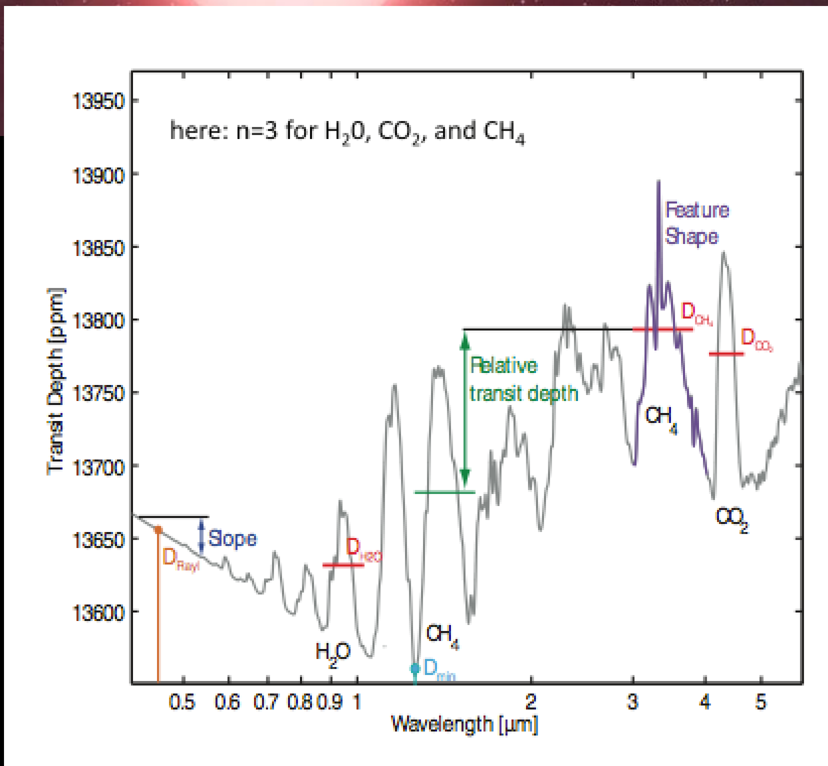


Redfield *et al.* 2008

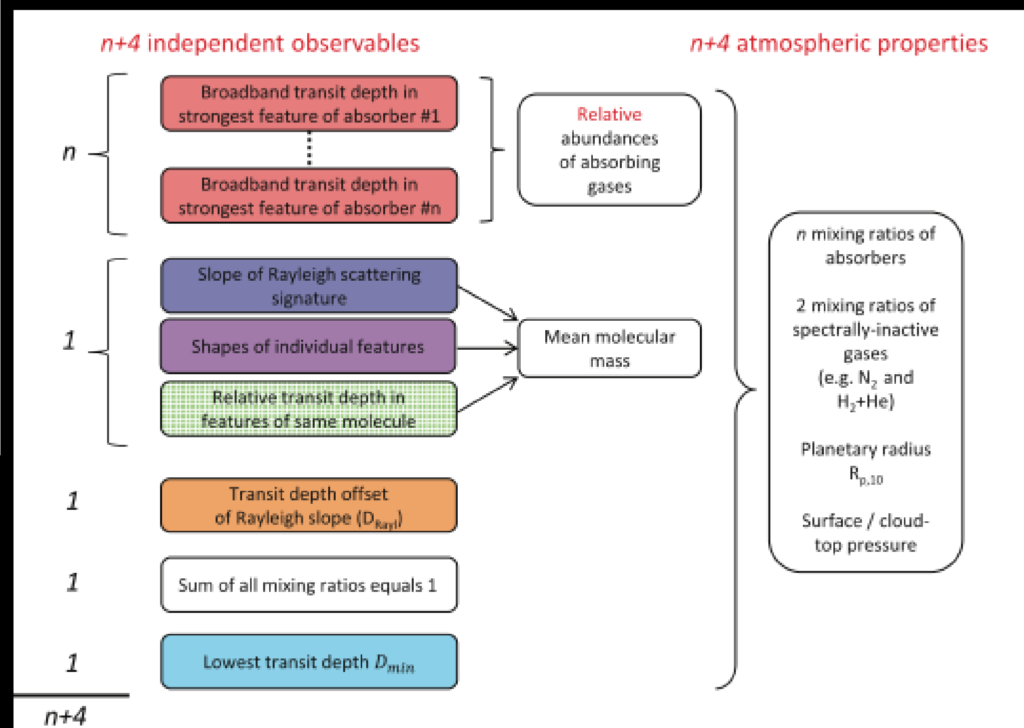
- Take multiple in-transit and out-of-transit spectra
- Observe bright calibrator stars in order to account for telluric absorption
- Excess absorption during transit spectra is due to exoplanet atmosphere
- A planetary transmission spectrum = (spectrum of the star and planet during transit) / (spectrum of the star at occulation)
- Total flux of spectrum would be obtained from subtracting (Planet+star spectrum) – Star Spectrum, and it gives information on atmospheric composition and temperature gradient (IR) or albedo(visible

Atmospheric Composition: Spectroscopy

- Relative depths of in-transit / out-of-transit spectra → transit depth vs. wavelength



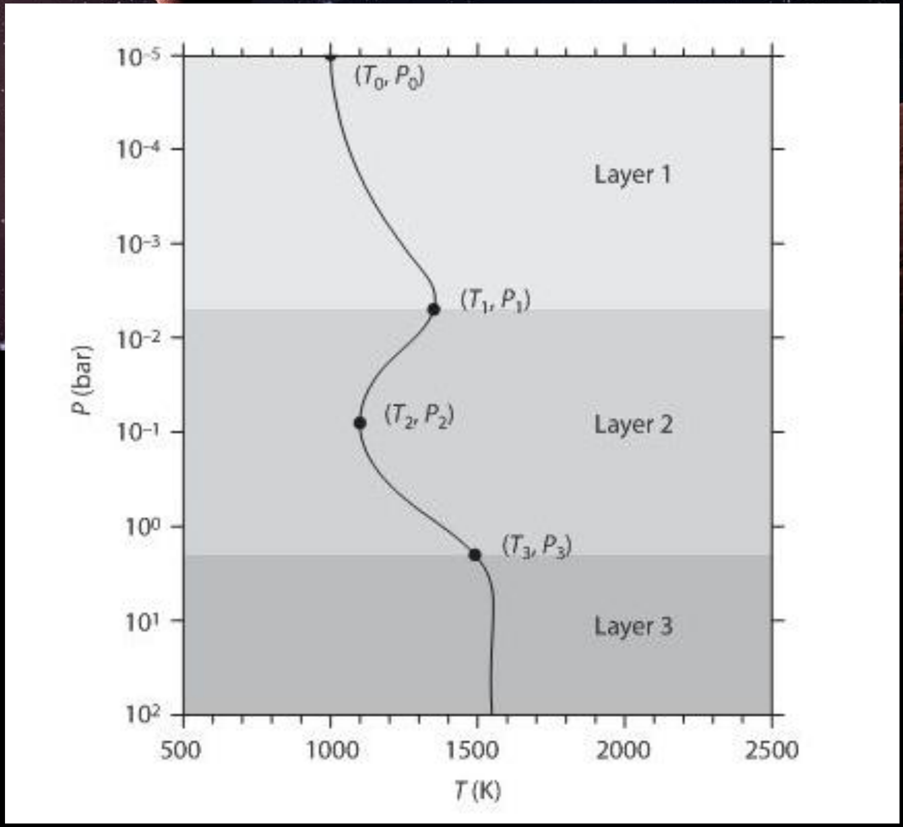
Benneke & Seager (2012)



Atmospheric Composition: Spectroscopy

Using Spectroscopy data we may describe:

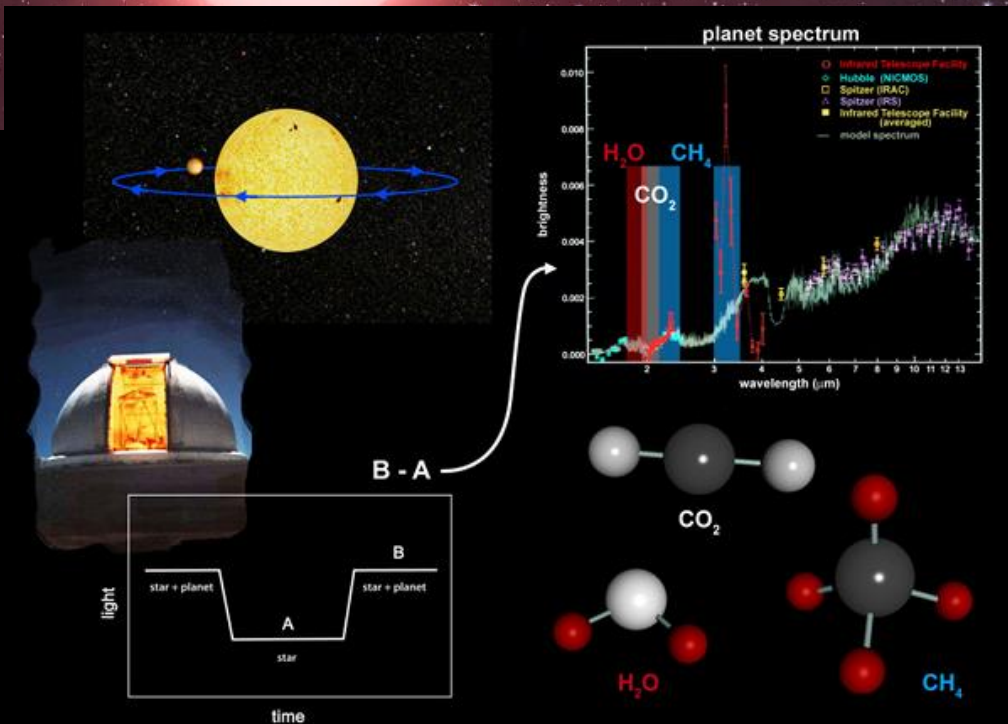
- Vertical atmospheric Pressure-Temperature structure of exoplanets from the existing models
- 3D Atmospheric circulation models based on fluid dynamics



Seager, Exoplanets Atmospheres (2010)

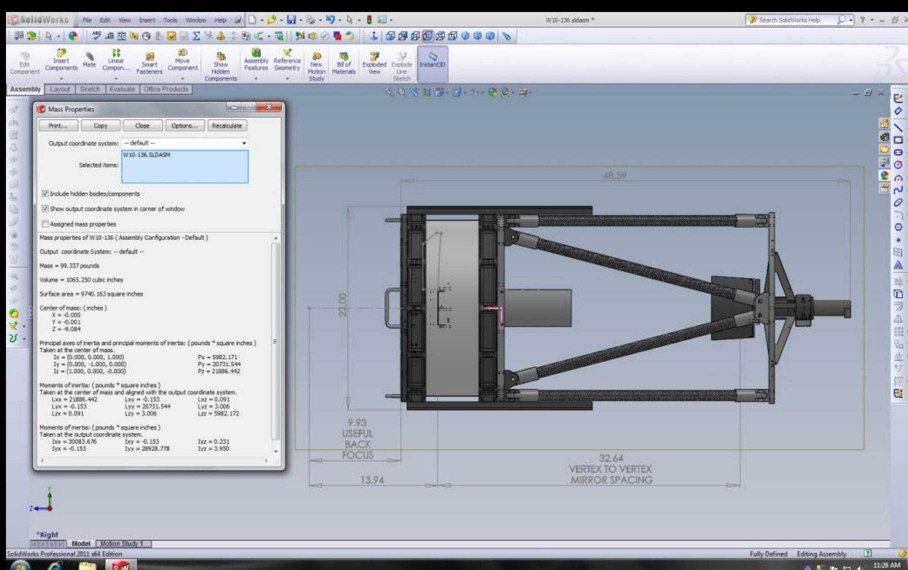
Atmospheric Composition: Mearth(mirth)

- Uses transit method to confirm exoplanets from list of 2,000 red dwarf stars.
- Observes M dwarf stars(<sun) to look for Earth sized planets(blocks more light of smaller stars).
- M dwarf stars are cooler than the sun so 'Earth-like' planets orbit much closer and more likely to pass in front of star.
- Specifically looking for planets with liquid water.
- Will use JWST to study atmosphere composition



Atmospheric Composition: Mearth(mirth)

- Use 8 computer controlled telescopes.
- Diameter: .40m
- .40m F/9 system
- 2048 x 2048 CCD's with a plate scale of 0.76 arc seconds/pixel
- Primary focuses directly onto CCD(Ritchey-Chretien).
- Custom filter allows wavelengths >715nm



Atmospheric Spectroscopic Analysis

- NESSI
  (New Mexico Tech Spectroscopic Survey Instrument)
  - Ground based multi-object spectrograph
  - Science goal: To take moderate resolution spectra of transiting exoplanet atmospheres in the infrared, where molecular constituents are abundant, in such a way as to be highly calibratable and repeatable (done only with space based spectrometers prior to 2009)
  - Operates in J, H, K bands (1.1 to 2.4 microns – near IR)
  - Resolution of R=1000 in each band
  - Lower resolution of R = 250 across entire J/H/K region
  - Mounted on 2.4 m telescope

Atmospheric Spectroscopic Analysis

- 2.4 m telescope
  - Elevation: 3200 m
  - Location: South Baldy, Magdalena, NM
  - f/2.03 primary (originally commissioned for Hubble)

Atmospheric Spectroscopic Analysis

- NESSI: Capabilities
  - Quickly assess transiting exoplanets during transits in the presence of the parent star’s flux
  - Stable over short (tracking) and long (repeat visit) timescales
  - Simultaneous coverage of both target and calibrators (multi-object capabilities)
  - On a dedicated platform that can be readily accessed so that transits can be measured whenever they happen, and readily as new missions identify new targets

Atmospheric Spectroscopic Analysis

- NESSI: Specs

Measurable	Design Goal
Telescope Focal Station	Nasmyth
Operational Wavelengths	1.1 to 2.4 microns (J/H/K)
Modes of Operation	Low - Res (R~250) across J, H, & K; Moderate - Res (R~1000) in each band; Imaging
FOV	Infrared: 12 arcmin; Optical: 4 arcmin
Pixel Scale	Infrared: 0.5 arcsec/pixel
Direct Imaging	Over entire FOV
Image Quality	EE80<1pixel = 1 arsec = 36 microns
Guiding	Optical at 1 - 5 Hz rate and 0.3 arcsec accuracy
System Throughput	20% minimum
Stability of Image at Mask	Due to drifts (derotator or telescope) 0.3 arcsec
Multi-object Apertures	3 to 5 arcsec, with MOS separations of 6.0 arcsec in the spatial direction
Masks in Wheel	Minimm of 8 exoplanet fields plus open and dark
Dewar Hold Time	Minumum 36 hrs

Atmospheric Spectroscopic Analysis

- NESSI
  - Will see first light summer 2013
  - Can theoretically do earth-size planets close in to the parent star (will start with hot Jupiters and work down in planet size)

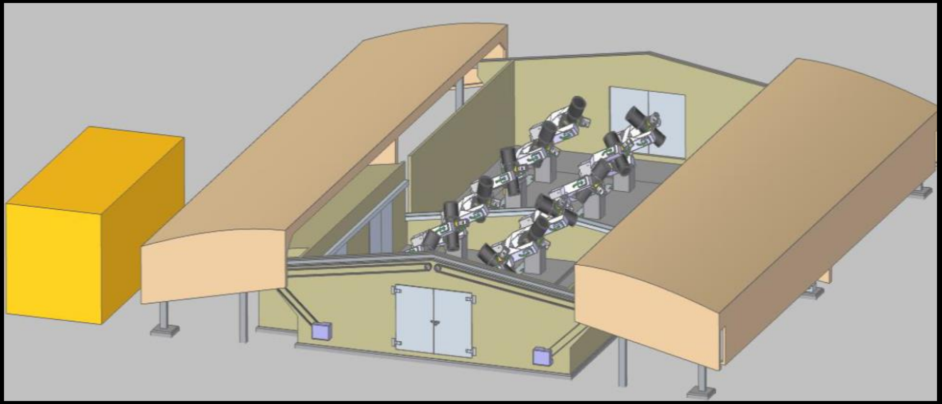
NGTS

- Objective:
  – Search for transiting planets in the size range of Neptune and below (diameters between 2-5 Earth size on bright stars)
- Completed by end of 2013

NGTS

Figure 7: View of the NGTS telescopes and their mount

Number of Telescope	12
Telescope	ASA custom 8” hyperbolic design
Telescope focal ratio	f/2.8
CCD	e2v 2kx2k DD chip, Ikon-L by Andor
Pixel size (μm)	13.5
Pixel size (arcsec)	4.97
FoV per telescope	8 square degrees
total FoV	87 square degrees
Mount type	OMI robotic mounts



	F & G	K	Early M	Late M	Total
10 mmag	4187	2671	411	56	7325
3 mmag	1840	640	69	8	2557
1 mmag	531	115	10	1	657

Table 3: Number of stars per type and achieved photometric accuracy in 8 square degrees FoV (l=227, b=-30)

mag	$R < R_{Jupiter}$	$R < R_{Neptune}$	$R < 2R_{Earth}$
Vmag<13	733	309	23
Vmag<15	3547	672	34
Imag<15	6288	823	55

Table 4: Number of stars for each limiting magnitude and planet size upper limit in 8 square degrees FoV (l=227, b=-30)

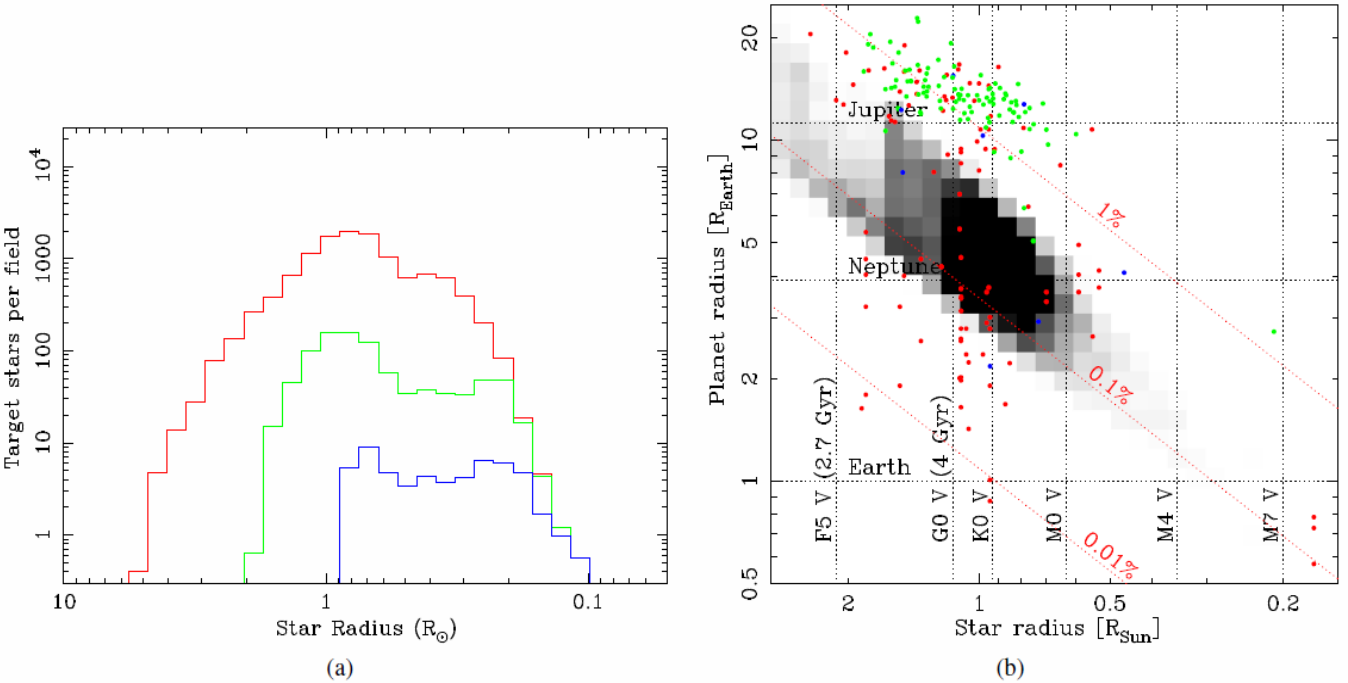


Figure 10: (a) Histograms of the numbers of stars detected per unit telescope as a function of spectral type for different detection thresholds depending on planets size: Blue $R < 2R_{Earth}$; Green $R < R_{Neptune}$; red $R < R_{Jupiter}$ (l=227, b=-30) (b) Iso-density plot of our stellar sample expressed in planet discovery space. Only stars with V magnitude brighter than 15th have been considered. The red dotted line indicates the depth of the transit. Green dots are planets discovered by ground based survey, Red dots are planets found by space based survey, blue one are the one discovered by radial velocity surveys.

NGTS

<u>Pink diamond:</u> ground base transiting planets (WASP and HAT)

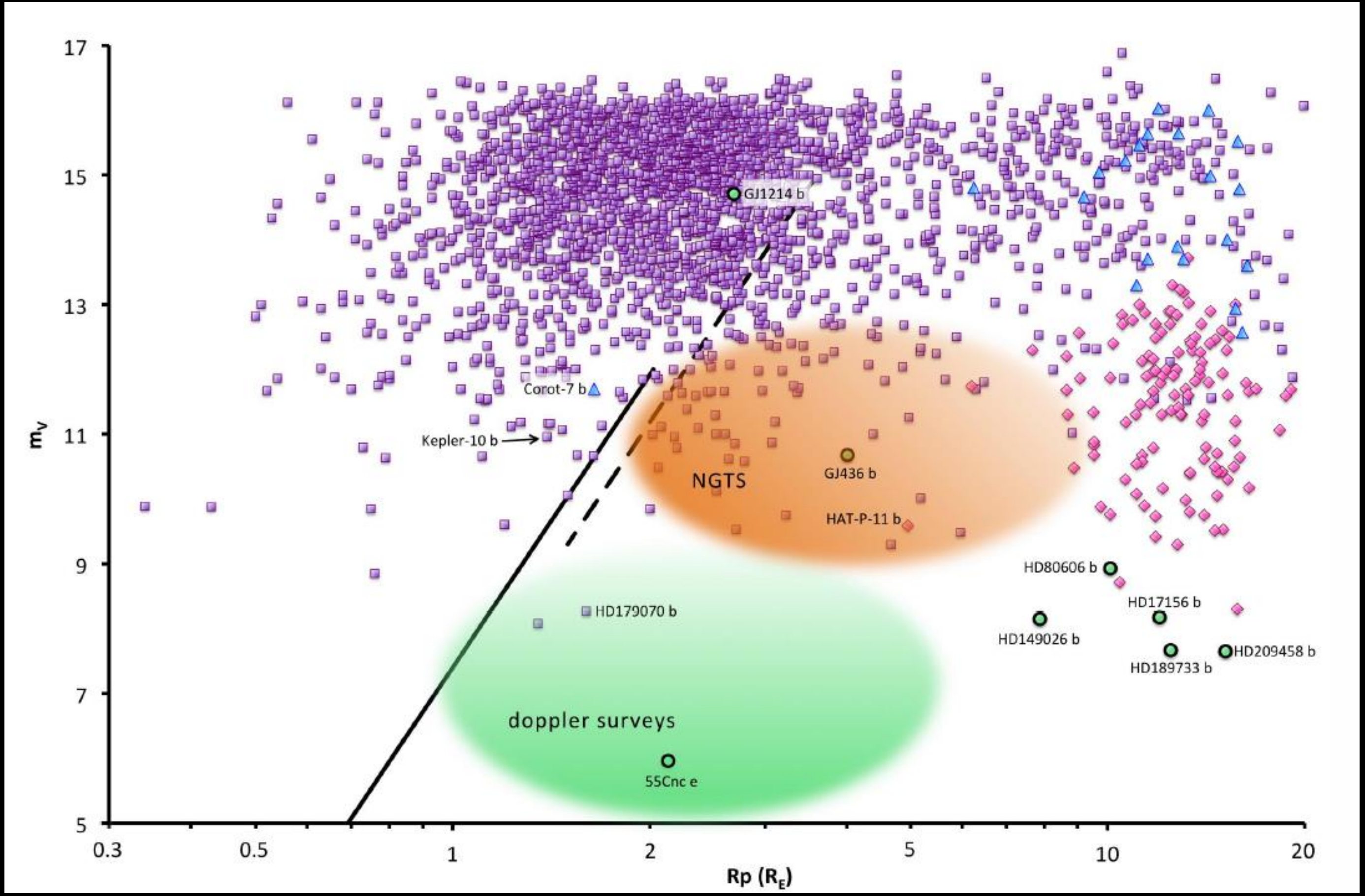
<u>Green:</u> planet in radial velocity survey that have been found transiting their star

<u>Blue triangles:</u> Corot transiting planets

<u>Violet square:</u> Kepler transiting planet candidates

<u>Orange area:</u> target search domain of NGTS

<u>Green area:</u> target regions of the precise Doppler search programs (HARPS)



Conclusion

- Why would we care for all of this?
  - These measurements help to confirm and characterize exoplents to further the study of other habital worlds as we continue to search for other life in the universe and try to answer the question “are we alone?”

Conclusion

- RV
  - Used to confirm planet candidates
  - Finds minimum mass of exoplanets
- Finding mass of exoplanets
  - Through the use of a combination of RV and a planets transit we are able to find the exact their mass
  - For larger planets that are non-transiting we are able to use high resolution RV by looking at the CO and CH_4
- Spectroscopy
  - Vertical atmospheric Pressure-Temperature structure of exoplanets from the existing models
  - 3D Atmospheric circulation models based on fluid dynamics

Corrections

Locations of Radial Velocity Confirmation and Spectroscopy Telescopes:

- Chile (VLT – ESPRESSO)
- Chile (HARPS)
- Hawaii (Keck)
- New Mexico (NESSI)

Specifications and Uses for each instrument:

- **VLT – ESPRESSO spectrograph** – with extreme radial velocity confirmation – more advanced HARPS - 10cm/s rv precision; (coming online soon); will be optimized for planets of a few Earth-size planets around quiet G – M type stars; spectral range: 380-780nm
- **ESO La Silla Observatory - HARPS** – use for radial velocity confirmation; 0.97m/s rv precision - 3.6m aperture; optimized for planets on the order of 10x Earth mass
- **Keck – HIRES spectrograph** – use for radial velocity confirmation; 1m/s rv precision 2 10m apertures; spectral range: 0.3-1 microns; optimized for ~ Jupiter size planets
- **MRO – NESSI spectrograph** –use for spectroscopic analysis; 2.4m aperture (coming online soon); optimized for hot Jupiters but will theoretically be able to work down to Earth-size planets; only used for studying spectral features – the resolution will not be good enough for radial velocity

Corrections

Strategy for Utilizing Each Instrument:

Observing times will be determined by when we can get time on the telescopes because all but NESSI are not dedicated platforms – we would have to apply for time. We believe that, given the layout of our initial system used to detect transits (from Project 1) and the proximity of these observatories chosen for confirmation measurements, we will have no issues with seeing the 30° by 180° patch of sky (the galactic plane) and will therefore, theoretically, be able to look at all exoplanet candidates if given enough time.

How to Partition Off Exoplanet Candidates to the Chose Facilities for RV Confirmation:

Brighter candidates will go to facilities with smaller apertures and lower SNR capabilities

- HARPS

Dimmer candidates will go to facilities with larger apertures and higher SNR capabilities

- ESPRESSO
- Keck

Decided not to use MEARTH and NGTS because both are only capable of transit detections, and NESSI will only be doing spectroscopy.