2020 Sagan Exoplanet Virtual Workshop on Extreme Precision Radial Velocity:

Why Are RVs Important?

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Steward Observatory

THE UNIVERSITY OF ARIZONA

July 20, 2020

Welcome and Thanks from the SOC!

- **Local Organizing Committee (LOC)**
  - **Elise Furlan**
  - **Ellen O'Leary**
  - **Wendy Burt**
  - **Megan Crane**
  - **Dawn Gelino**

- Hands-On Session Coordinators
  - Nathan Hara
  - BJ Fulton

- Scientific Organizing Committee (SOC)
  - Heather Cegla (Co-Chair)
  - Chad Bender (Co-Chair)
  - Chas Beichman
  - Eric Ford
  - BJ Fulton
  - Elise Furlan
  - Dawn Gelino
  - Andrew Howard
  - Stephanie Leifer
  - Andreas Quirrenbach
  - Johanna Teske

And the more than 500 participants world-wide.

Overview of the Workshop

- **Lectures:**
  - **Monday, July 20:**
    - Fundamentals of PRV, Error Budgets, and Instrumentation
  - **Tuesday, July 21:**
    - Fundamentals of Data Analysis and Statistical Significance
  - **Wednesday, July 22:**
    - Stellar and Telluric Signals and their impact on EPRV
  - **Thursday, July 23:**
    - Characterizing Planets

- **Panel Discussions:** Mon, Tues, Wed, Thurs
- **Hands-On Sessions:** Mon, Tues, Wed, Fri
- **Lunch (or timezone appropriate snack/meal) with the speakers:** Fri

So, Why Are RVs Important?

Let’s set the stage with some history…

The Beginnings of Stellar Variability as a Tool for Characterization

- Astronomers have long known that some stars vary in brightness over short time periods (days, months, years – e.g. human lifetimes)
- 1783: John Goodricke reported* in a letter that he had measured periodic dimming in the brightness of Algol.
  - The events lasted *“about seven hours”* and occurred *“every two days and twenty-one hours”*
  - *The star had been previously reported to vary in 1695, but Goodricke is the first reported account of periodicity (a.k.a* ***Characterization****)*

**Philosophical Transactions of the Royal Society of London, vol 73, pg 474-482*

The Beginnings of Stellar Variability as a Tool for Characterization

If it were not perhaps too early to hazard even a conjecture on the cauſe of this variation, I ſhould imagine it could hardly be accounted for otherwiſe than either by the interpoſition of a large body revolving round Algol, or ſome kind of motion of its own, whereby part of its body, covered with ſpots or ſuch like matter, is periodically turned towards the earth. But the intention of this paper is to communicate facts, not conjectures; and I flatter myſelf that the former are remarkable enough to deſerve the attention and farther inveſtigation of aſtronomers.

**Philosophical Transactions of the Royal Society of London, vol 73, pg 474-482*

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Proposal for a Project of High-Precision Stellar Radial Velocity Work

Otto Struve, 1952, in The Observatory

One of the burning questions of astronomy deals with the frequency of planet-like bodies in the galaxy which belong to stars other than the Sun.

But how should we proceed to detect them ?

- Struve argued that the astrometric techniques popular in the time (e.g., by Strand, Van de Kamp and others) required such precise measurements that they could only be applied to an extremely small number of stars.

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There seems to be at present no way to discover objects of the mass and size of Jupiter; nor is there much hope that we could discover objects ten times as large in mass as Jupiter, if they are at distances of one or more astronomical units from their parent stars.

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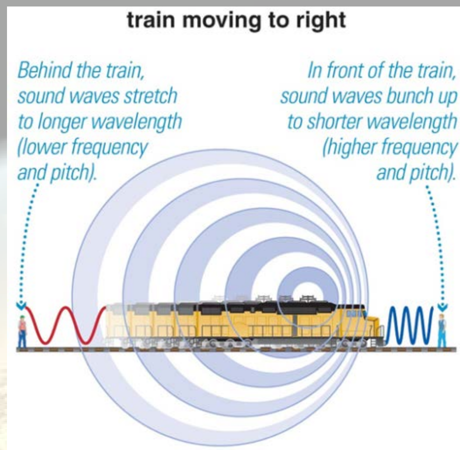
But there seems to be no compelling reason why the hypothetical stellar planets should not, in some instances, be much closer to their parent stars than is the case in the solar system. It would be of interest to test whether there are any such objects.

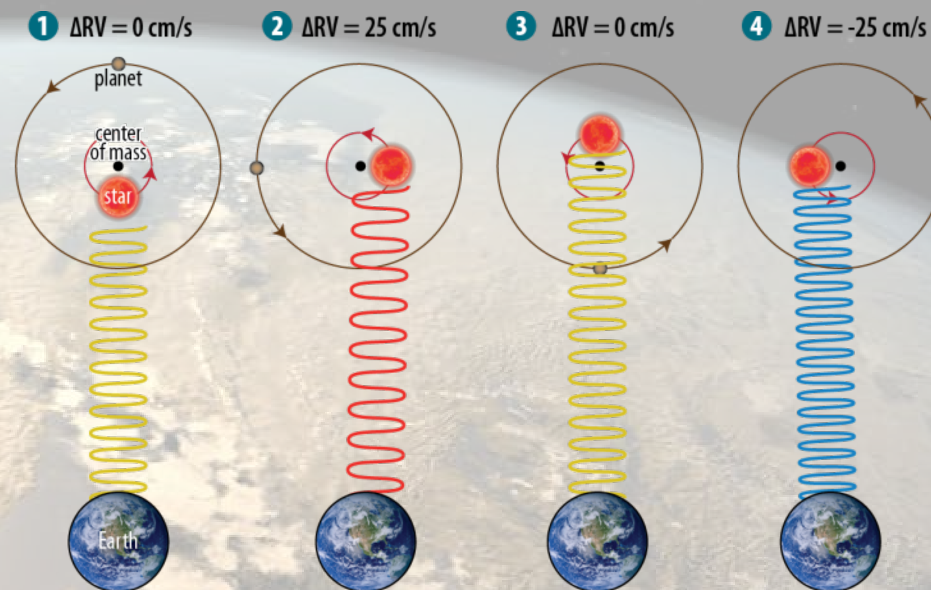
We know that *stellar* companions can exist at very small distances. It is not unreasonable that a planet might exist at a distance of 1/50 astronomical unit, or about 3,000,000 km. Its period around a star of solar mass would then be about 1 day.

We can write Kepler's third law in the form $V^3 \sim \frac{1}{P}$. Since the orbital velocity of the Earth is 30 km/sec, our hypothetical planet would have a velocity of roughly 200 km/sec. If the mass of this planet were equal to that of Jupiter, it would cause the observed radial velocity of the parent star to oscillate with a range of $\pm$ 0·2 km/sec—a quantity that might be just detectable with the most powerful Coudé spectrographs in existence. A planet ten times the mass of Jupiter would be very easy to detect,

More details on Instrumentation from Andreas Quirrenbach later this morning!

Doppler Velocimetry Primer



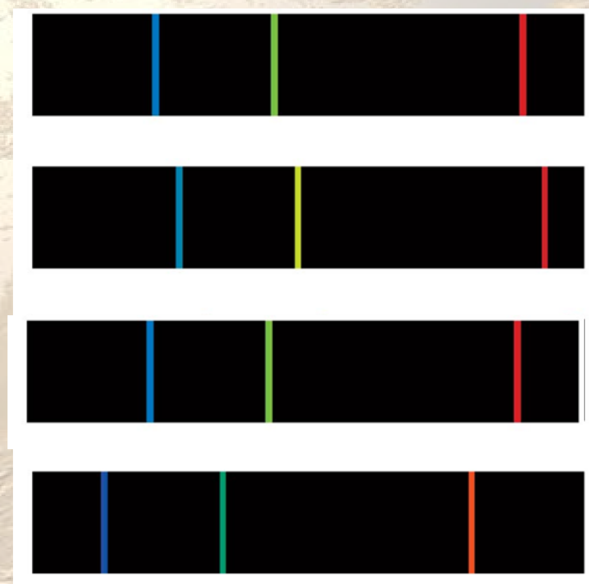


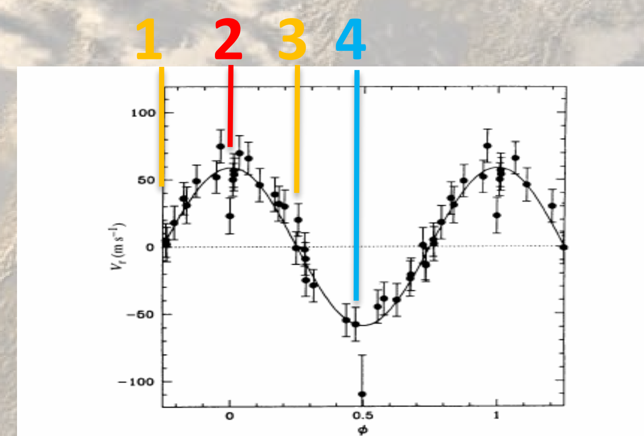
1 - Rest

2 - Redshift

3 - Rest

4 - Blueshift





Measuring the Doppler Motion of a Star Yields the Mass of the Companion

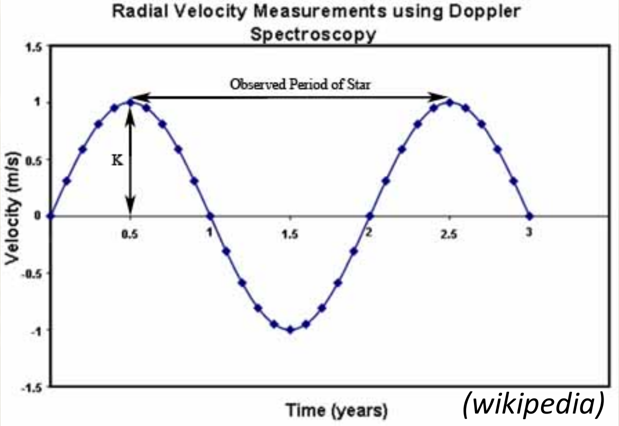
This is a Dynamical Mass. It is valuable because it is a fundamental quantity, and can be derived mostly independent from stellar evolution models.

Starting with Kepler's 3rd Law: $\frac{a^3}{P^2} = \frac{G(M_1+M_2)}{4\pi^2}$,

we can derive the binary mass function: $f = \frac{M_2^3 \sin^3 i}{(M_1+M_2)^2} = \frac{PK^3}{2\pi G}(1-e^2)^{\frac{3}{2}}$,

Where $K = v_1 \sin i$

For an exoplanet, where $M_1 \gg M_2$, $f \approx \frac{M_2^3 \sin^3 i}{M_1^2}$



(wikipedia)

More details from Debra Fisher (next) and Jason Wright (Tuesday)

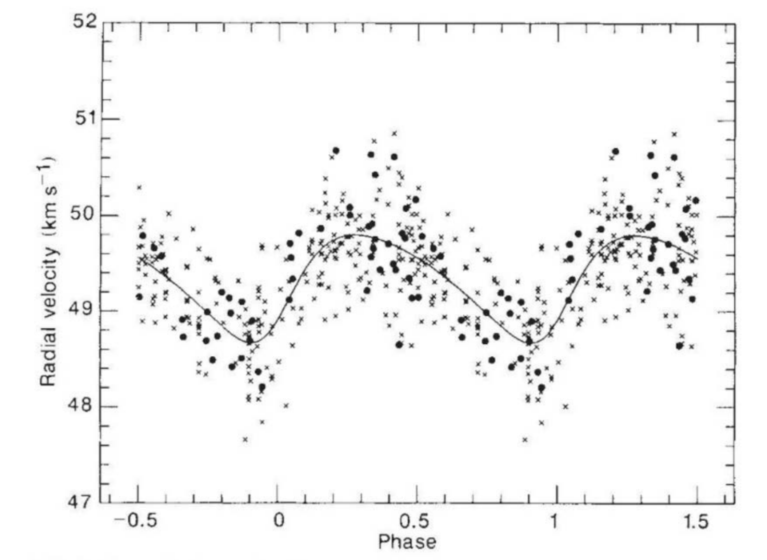
The unseen companion of HD114762: a probable brown dwarf

David Latham, Tsevi Mazeh, Robert Stefanik, Michel Mayor & Gilbert Burki

Nature, 1989, 339, 38

First Gen. precision RV spectrometers were surveying nearby stars

"The … period of 84 days places the companion in an orbit similar to that of Mercury … the low velocity amplitude of … 0.6 kms^{-1} implies that the mass of the companion may be as low as … 11 Jupiter masses. … the **companion is probably a brown dwarf, and may even be a giant planet**."



GAIA DR1 astrometry was used (Kiefer 2019, A&A 632, L9) to derive an orbital inclination of only ~5°, which implies a mass of ~141 $M_{Jupiter}$ (so, not a planet).

An RV Revolution in the 1990s leads to the first RV discovered planet

(and the 2019 Nobel Prize in Physics!)

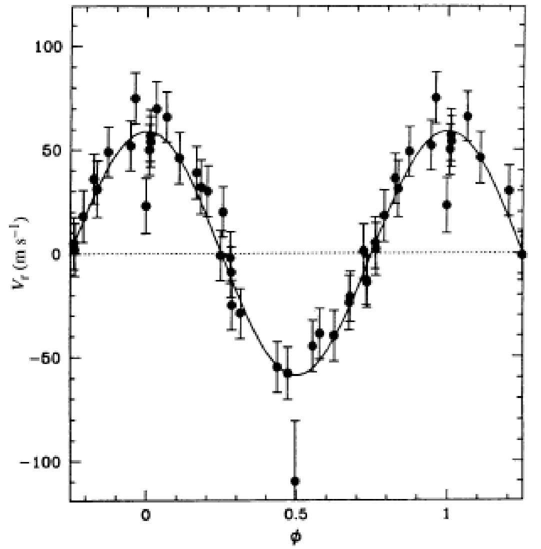
A Jupiter-mass companion to a solar-type star

Michel Mayor & Didier Queloz

Geneva Observatory, 51 Chemin des Maillettes, CH-1290 Sauverny, Switzerland

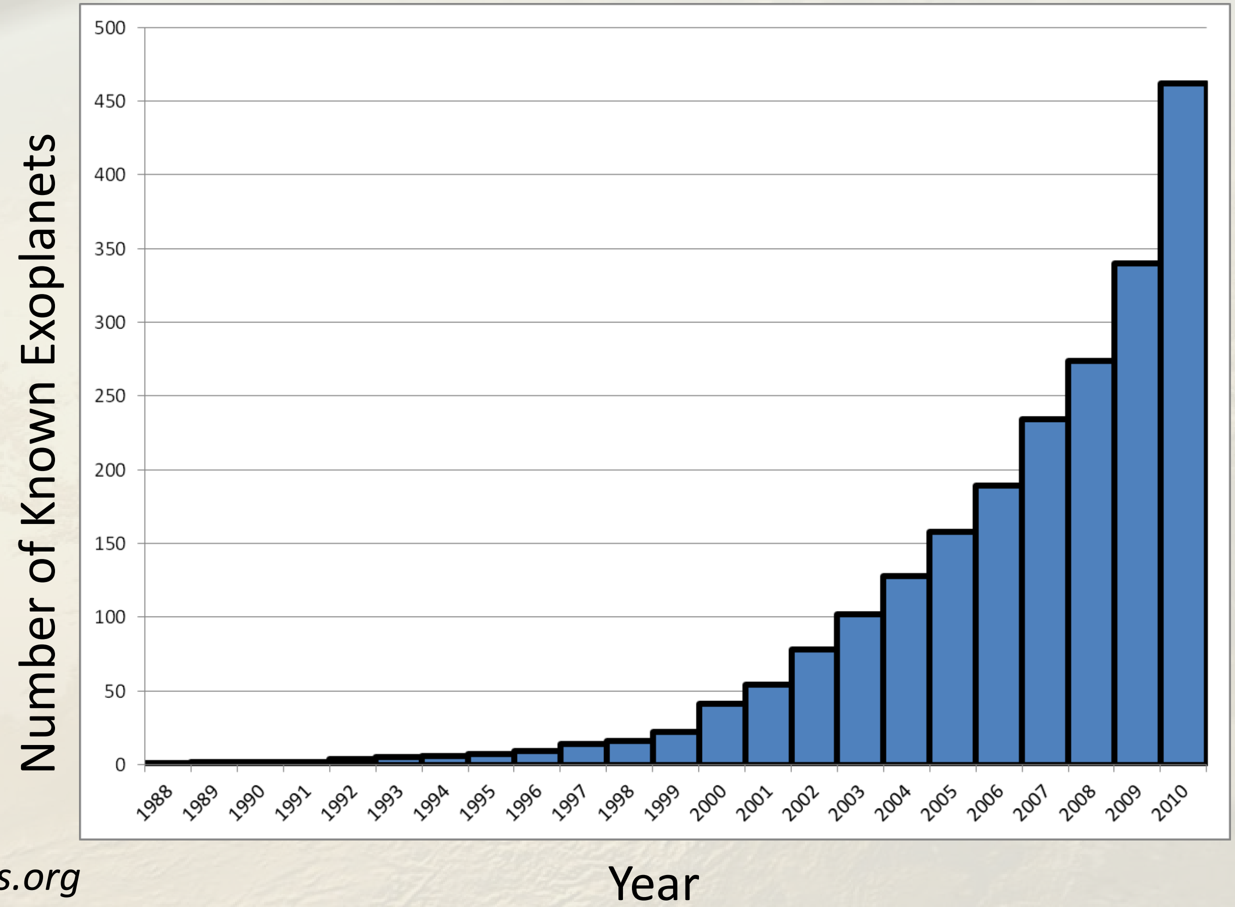
Nature 1995, 372, 355

The presence of a Jupiter-mass companion to the star 51 Pegasi is inferred from observations of periodic variations in the star's radial velocity. The companion lies only about eight million kilometres from the star, which would be well inside the orbit of Mercury in our Solar System. This object might be a gas-giant planet that has migrated to this location through orbital evolution, or from the radiative stripping of a brown dwarf.



The Nobel Prize in Physics 2019 was awarded "for contributions to our understanding of the evolution of the universe and Earth's place in the cosmos" with one half to James Peebles "for theoretical discoveries in physical cosmology**", the other half jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."**

Steadily Increasing Exoplanet Discoveries: Mostly from Radial Velocities



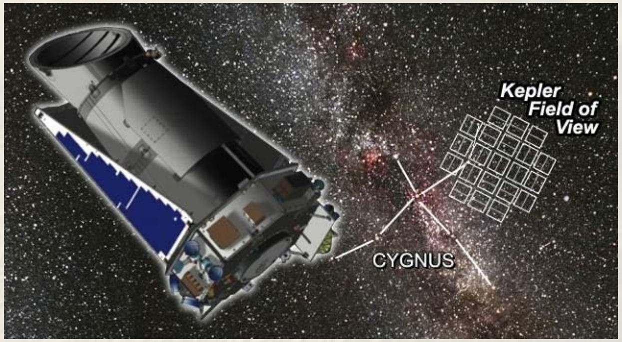
exoplanets.org

The Wide-Field Precision Photometery Revolution Started in the Early 2000s

Again, (mostly) predicted by Struve in 1952:

> There would, of course, also be eclipses. Assuming that the mean density of the planet is five times that of the star (which may be optimistic for such a large planet) the projected eclipsed area is about 1/50th of that of the star, and the loss of light in stellar magnitudes is about 0·02. This, too, should be ascertainable by modern photoelectric methods, though the spectrographic test would probably be more accurate. The advantage of the photometric procedure would be its fainter limiting magnitude compared to that of the high-dispersion spectrographic technique.

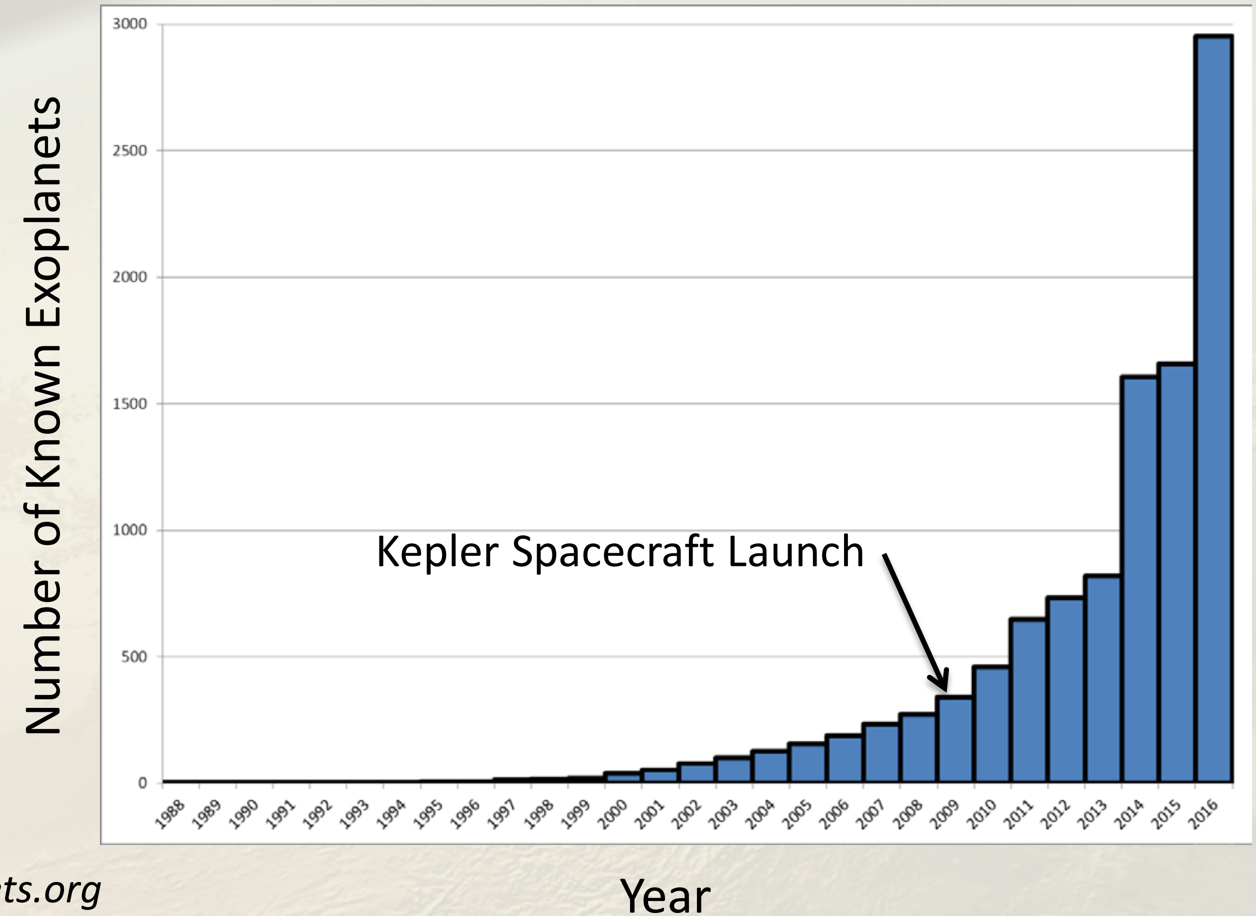
CoRoT



Kepler

TESS

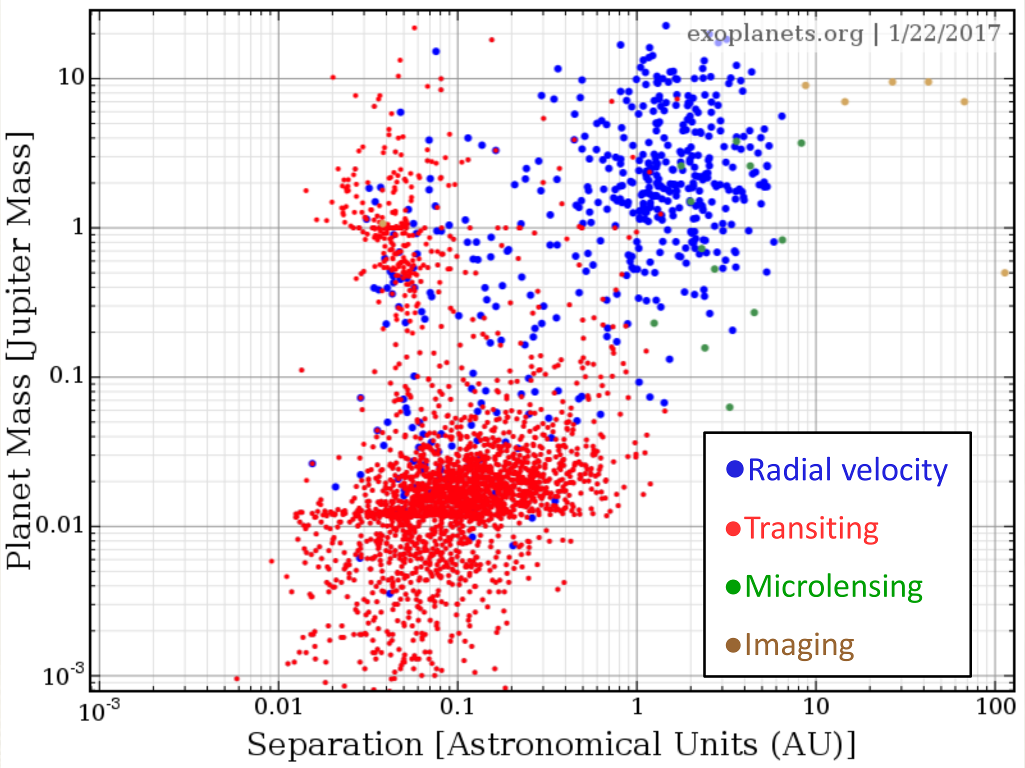
Transits Yield A Huge Increase in Planets: Are RVs Still Relevant?



exoplanets.org

The Exoplanet Landscape from Different Measurement Techniques

- Multiple techniques have started to fill out the exoplanet parameter space.
- Transits have discovered the most planets, and directly constrain the planet/star radius ratio.
- Measuring the mass of a planet usually* requires detection with another technique – RVs are the most tractable for terrestrial planets

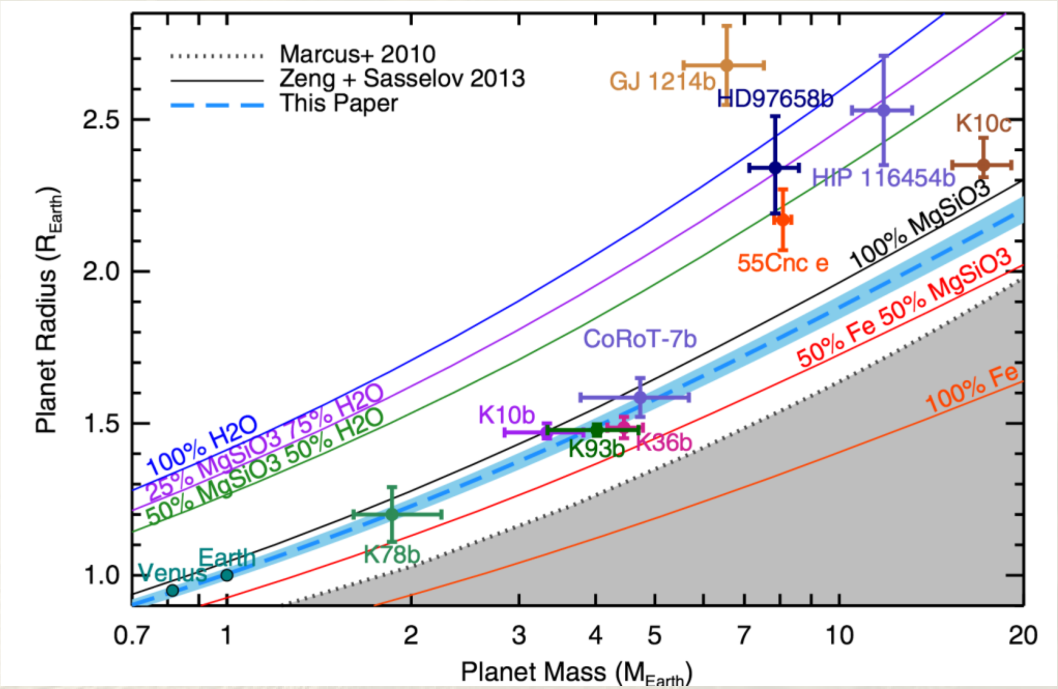


*Caveat: Dynamical masses have been derived for a few multi-planet, multi-transit systems with transit-timing variations (e.g. Kepler-16)

With Both Mass and Radius, We Can Start to Characterize Planet Interiors

- With radius alone, all you know is the *size* of a planet and it's distance from the star.
- Add a precise mass measurement , and you now have a bulk density.
- Start to constrain planet composition and formation models

Dressing et al. 2015, ApJ, 800, 135



Ask Courtney Dressing about this on Thursday!

The Precision Radial Velocity Spectrometer Sensitivity Landscape

- *The 1990s – 2000s 2nd generation spectrometers have precisions of ~one – a few m/s*
  - HARPS is the most precise (~50-70 cm/s at best)
- *The 2010s saw development of 3rd generation instruments, just now coming on line, with goals of ~30 cm/s or better*
  - NEID, EXPRES, ESPRESSO, KPF and others
- *It also triggered construction of near-infrared spectrographs that target M-dwarfs, where the signal from a habitable zone Earth is ~1 m/s*
  - (Carmenes, HPF, MaroonX, SPIROU, IRD, CSHELL, iLocator)

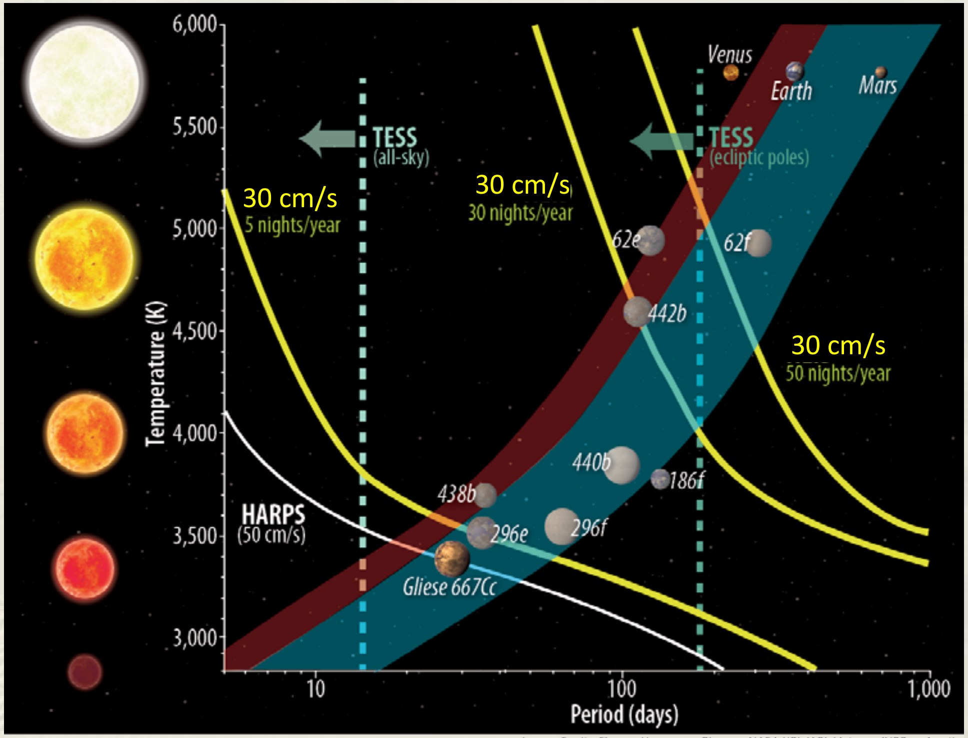
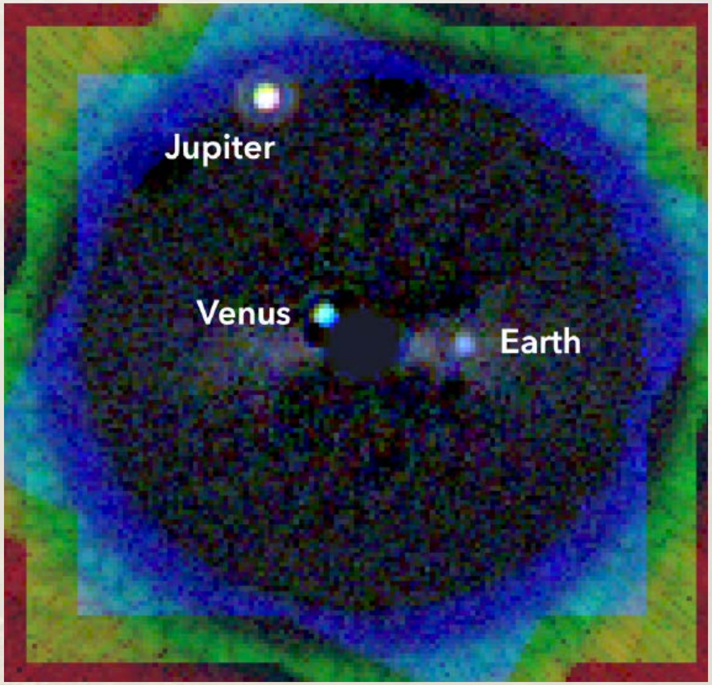


Image Credit: Chester Harman Planets: NASA/JPL/APL/Arizona/UPR at Arecibo

What do we mean by Extreme Precision Radial Velocity (EPRV)?

- *Sufficient to detect Earth-mass planets in the Habitable-Zones of Sun like stars*
  - The Earth induces a 10 cm/s Doppler wobble on the Sun
- *Requires observations on 10s to 100s of nights/year at <<50 cm/s precision*
  - High cadence observations from sites worldwide, over years
- *These planets represent the top targets for future direct imaging missions (e.g. LUVOIR, HABEX)*

Ask Sam Halverson about the error budget needed for a 10 cm/s measurement in the panel later this morning!



Simulation of the inner solar system from a distance of 12.5 parsecs with the LUVIOR-A space telescope concept. (From the LUVIOR Final Report)

Why is this Worthwhile?

- Science Questions:
  - ***How do stars and planets form and evolve?***
    - EPRV can provide a more complete census of a diverse population of planets, including terrestrial mass, and measurements of their bulk composition.
      See Thursday talk by Courtney Dressing
  - ***What environments are potentially habitable?***
    - *EPRV complements atmospheric spectroscopy, by characterize planetary bulk properties to provide context for atmospheric measurements of biosignatures.*
      See Thursday talks by Natasha Batalha, Jayne Birkby, and Jim Kasting
- Humanity Questions:
  - ***Is there life on planets outside of the Solar System?***
    - EPRV precursor observations can reduce the required mission durations of LUVOIR or HABEX-like direct imaging missions to achieve their requirements for characterizing planets by 3X!
      Ask Scott Gaudi about this on Wednesday!

So How Do We Get There?

Goal: Build on lessons from the 2nd and 3rd generation spectrometers to build ***a 4th generation with precision of ~10 cm/s on bright stars***, and intrinsic stability of a few cm/s, that can discover Earth-twins, explore terrestrial planets as a population, AND support space based imaging missions

- Chart a technology roadmap to get us there: The NASA-NSF EPRV Working Group – ***Scott Gaudi on Wednesday***
- Learn how to robustly combine huge data sets from multiple instruments taken under varying condition and identify weak signals - ***Nathan Hara on Tuesday***
- Use current instrumentation, including solar telescopes on 3rd generation spectrometers, to better understand solar physics and its impact on RVs - ***Heather Cegla, Annelies Mortier, and Jenn Burt on Wednesday***
- Collaborate with atmospheric scientists to mitigate the impact of tellurics on RVs ***– Cullen Blake on Wednesday***
- ***Recruit a new generation of students and postdocs to work on this endeavor – hopefully many of you attending this workshop!***