MERCURY IN TRANSIT

EXOPLANETS in TRANSIT

Transits reveal planets orbiting other stars.

Definitions:

Exoplanet: A planet orbiting a star other than our Sun.
Transit: A planet passing in front of a star, from our perspective.
Transit Method: A technique for finding exoplanets by watching distant stars for temporary drops in brightness.
Period or Orbital Period: The time it takes for a planet to complete one orbit around its star once.

The Transit Method

When a planet passes in front of a star – a *transit* – some of the star's light will be blocked by that planet. If we are watching carefully, we can see this small dip (see Figure 1).

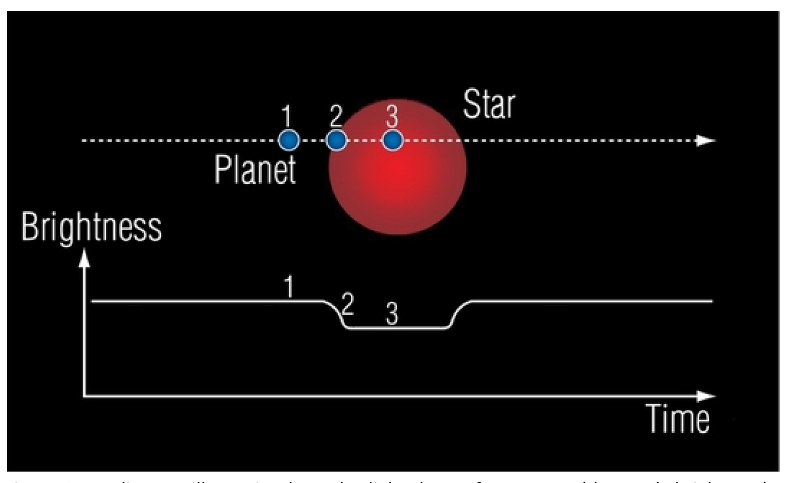


Figure 1: A diagram illustrating how the light detect from a star (the star's brightness) changes as a planet moves between us and the star. Credit: *NASA, ESA, G. Bacon (Space Telescope Science Institute)*

- **Position 1:** Most of the time, there will be no planet in front of the star, and we see all of the star's light.
- **Position 2:** The planet is starting to pass in front of the star. The amount of time it takes to be fully in front of the star tells us about the size and speed of the planet.
- **Position 3:** The planet is now fully transiting in front of the star. The amount of light it blocks is constant until it reaches the edge of the star. The time this takes tells us about the speed of the planet and size of the star. The amount of light blocked tells us how big the planet is relative to the star.

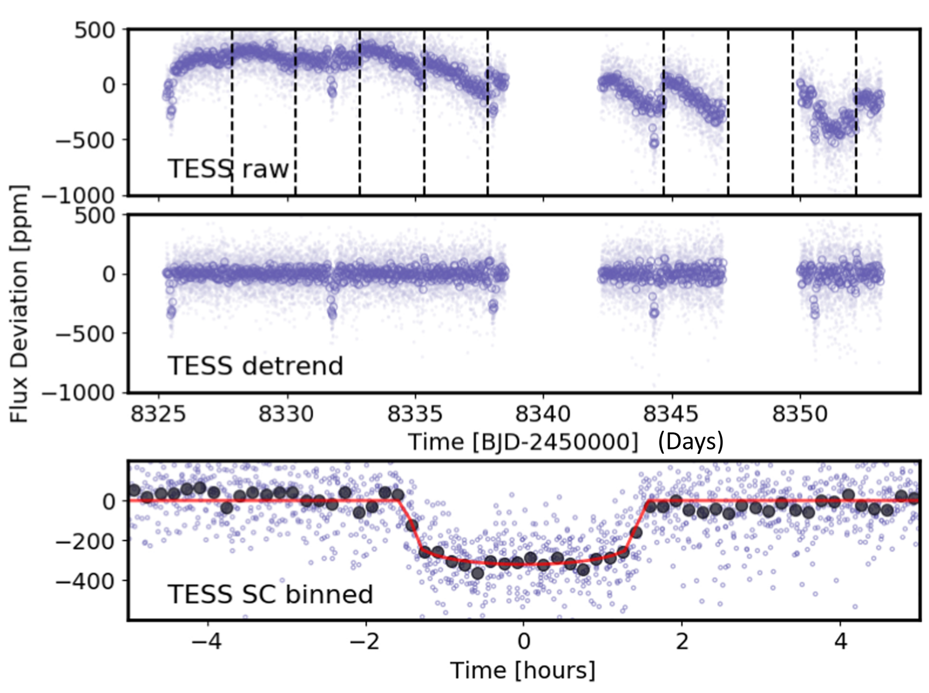


Figure 2: Actual data for an exoplanet detected by the transit method (ppm = parts per million). The top panel is the raw data, the middle panel is the data corrected for fluctuations in the telescope. The bottom panel is each transit added on top of each other to get a clear view of the transit. [This is Fig. 2 of "*TESS DISCOVERY OF A TRANSITING SUPER-EARTH IN THE π MENSAE SYSTEM*", Chelsea Huang, et al. (2018).]

- By seeing multiple "dips," we learn the orbital period of the planet.
- Astronomers need **three** regularly-spaced "dips" to know a planet exists – otherwise, we might be looking at "sunspots," asteroids in our own Solar system, or even two different planets!
- Note how small the change in the star's brightness appears: a few hundred parts per million (ppm)! (About 4 x 10^{-4}, to be precise)

Current Efforts

- **TESS (Transiting Exoplanet Survey Satellite)**: The successor to the productive KEPLER space telescope, TESS is currently the most productive exoplanet-finder (see below).
- **Gaia**: The European Space Agency's powerful space telescope designed to precisely measure distances to *billions* of stars. While studying stars to measure distances (through a technique called *parallax*), Gaia has found, and will continue to find, transiting exoplanets.
- **LSST (Large Synoptic Survey Telescope)**: The goal of LSST (estimated to go online – "first light" – in 2020) is to map the entire Southern sky (since it is in Chile) every three days, looking for changes. Exoplanet transits will be one of the changes that LSST will be able to find.
- **JWST (James Webb Space Telescope)** and **HST (Hubble Space Telescope):** The Hubble Space Telescope is currently used to follow-up on other observations in order to confirm the existence of exoplanets. Once JWST launches and is in operation, it will continue this mission.
- **Other:** Smaller research telescopes and surveys are also looking for exoplanets in small batches.

How Would Our Solar System Look to Other Observers?

What if astronomers around some distant star were looking at our Solar system, edge-on, and could see our planets and dwarf planets transiting in front of our Sun?

Jupiter is the largest planet (being about 10 times larger in diameter than Earth), and so would be the easiest planet to detect, blocking 1.4% of the Sun's light for about 30 hours (see Figure 3 and Table 1).

Note how much they would have to zoom in just to see Earth's transit!

Since astronomers need at least 3 transits to confirm the existence of a planet, distance astronomers would need to watch our Sun for 3 times the orbital period of each planet (Table 1) in order to detect it.

They would have to watch for 3 years to detect Earth, and about 36 years to detect Jupiter!

Table 1: Transit Properties for Solar System Planets and Dwarf Planets

OBJECT NAME	TRANSIT DURATION	ORBITAL PERIOD	SUN'S LIGHT BLOCKED	SUN'S LIGHT BLOCKED (sci. notation)
Mercury	7 hours	88 days	16 ppm	1.6 x10^{-5}
Venus	9.5 hours	7.5 months	100 ppm	1.0 x10^{-4}
Earth	11 hours	1 year	110 ppm	1.1 x10^{-4}
Mars	14 hours	1.9 years	32 ppm	3.2 x10^{-5}
Ceres*	18.5 hours	4.6 years	0.61 ppm	6.1 x10^{-7}
Jupiter	30 hours	11.9 years	1.4 %	1.4 x10^{-2}
Saturn	37.5 hours	29.4 years	0.94 %	9.4 x10^{-3}
Uranus	2.1 days	84 years	0.17 %	1.7 x10^{-3}
Neptune	2.6 days	165 years	0.17 %	1.7 x10^{-3}
Pluto*	2.9 days	248 years	3.9 ppm	3.9 x10^{-6}
Eris*	3.8 days	557 years	3.9 ppm	3.7 x10^{-6}

ppm = parts per million
* Dwarf planet

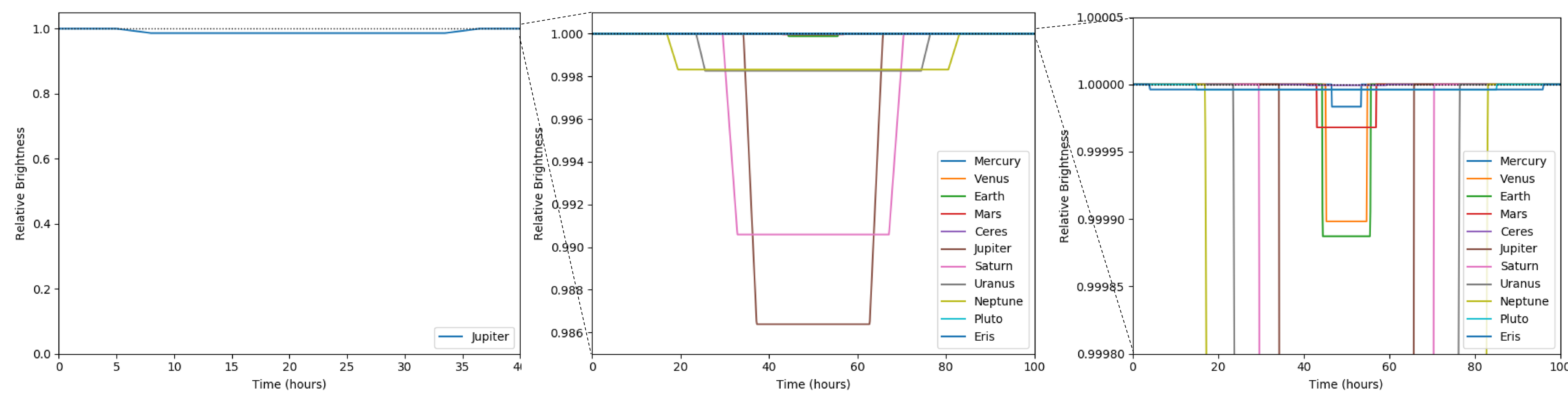


Figure 3: Simulated light curves for planets and dwarf planets orbiting our Sun. Note that these are "ideal," assuming no observational errors and no fluctuations in the Sun's output. The effects of moons, asteroids (or other planetesimals or debris), and rings (in the case of Saturn or Neptune) have been ignored. Planets were assumed to transit directly across the full diameter of the Sun. The geometry of transit ingress/egress has been simplified.

Over 4,000 Known Extrasolar Planets

Over 4,000 exoplanets have been confirmed to date. The majority of these have been detected by the transit method (Figure 4), but other methods have contributed as well (see next section, below). Current methods tend to favor finding higher-mass, lower-period planets (Figure 5). Low-mass planets may be the most common, but techniques and technology are not sensitive enough – yet!

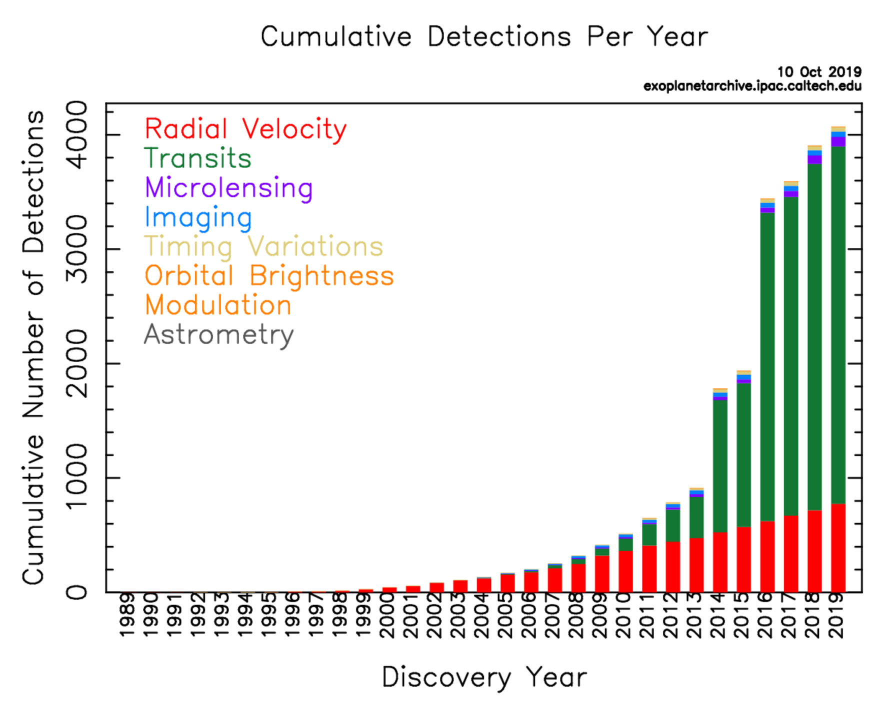


Figure 4: Total number of known exoplanets each year. Columns are colored according to the number of exoplanets found by each detection method.

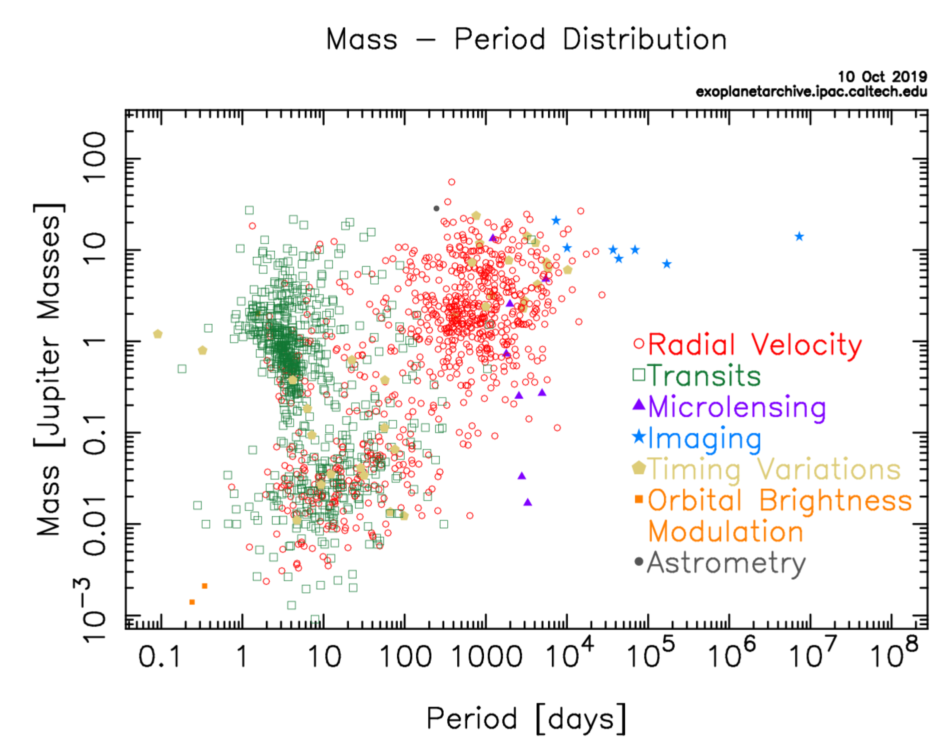


Figure 5: Masses and periods of known exoplanets. Each planet is plotted with a symbol and color representing the method used to discover that planet. Note that the radial velocity method has the easiest time finding high-mass planets, while the transit method favors finding short-period planets.

Other Methods to Detect Exoplanets

Radial Velocity Method: This method looks at the back-and-forth motion of a star (radial velocity) for a wobble caused by another mass. The method was the first used to find an exoplanet, 51 Pegasi b (shown below), resulting in the 2019 Nobel Prize in physics (see below).

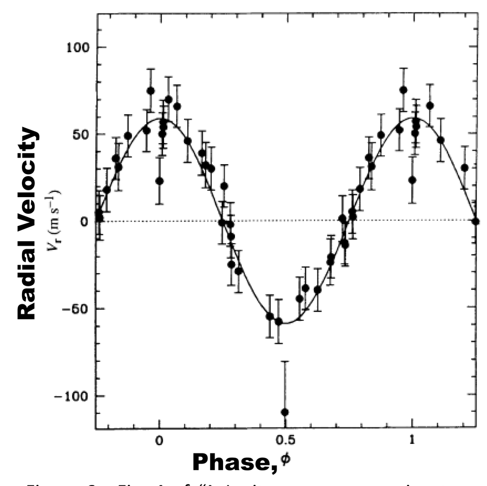


Figure 6: Fig. 4 of "A Jupiter-mass companion to a solar-type star," Mayor & Queloz (1995)

Gravitational Lensing: A star's gravity can act like a lens, magnifying light from a distant object behind it. When this happens, a distant star appears a few times bigger than usual for a short time. By carefully watching this jump in magnification, a smaller object (a planet!) orbiting the star may contribute to the lensing effect, resulting in a second, smaller jump in magnification.

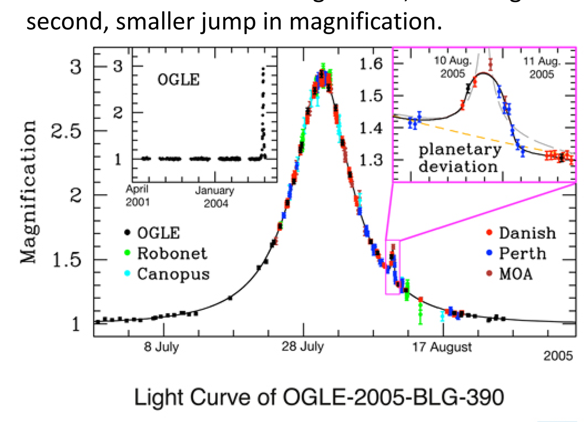


Figure 7: An European Southern Observatory example of the gravitational lensing detection method.

Direct Detection: With very careful observations, astronomers have been able to take direct pictures of a few planets. This is a very hard thing to do, as planets are very small and very, very dim, compared to their host star. To have a chance of seeing these planets, astronomers have to block the star's light (black blob in the image below). Even then, exoplanet Fomalhaut b is still just a little speck of light (inset).

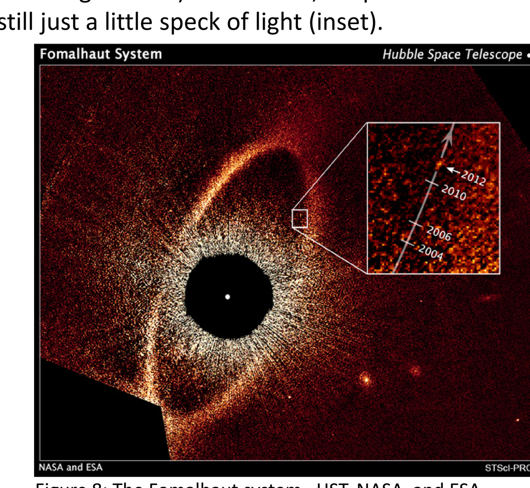


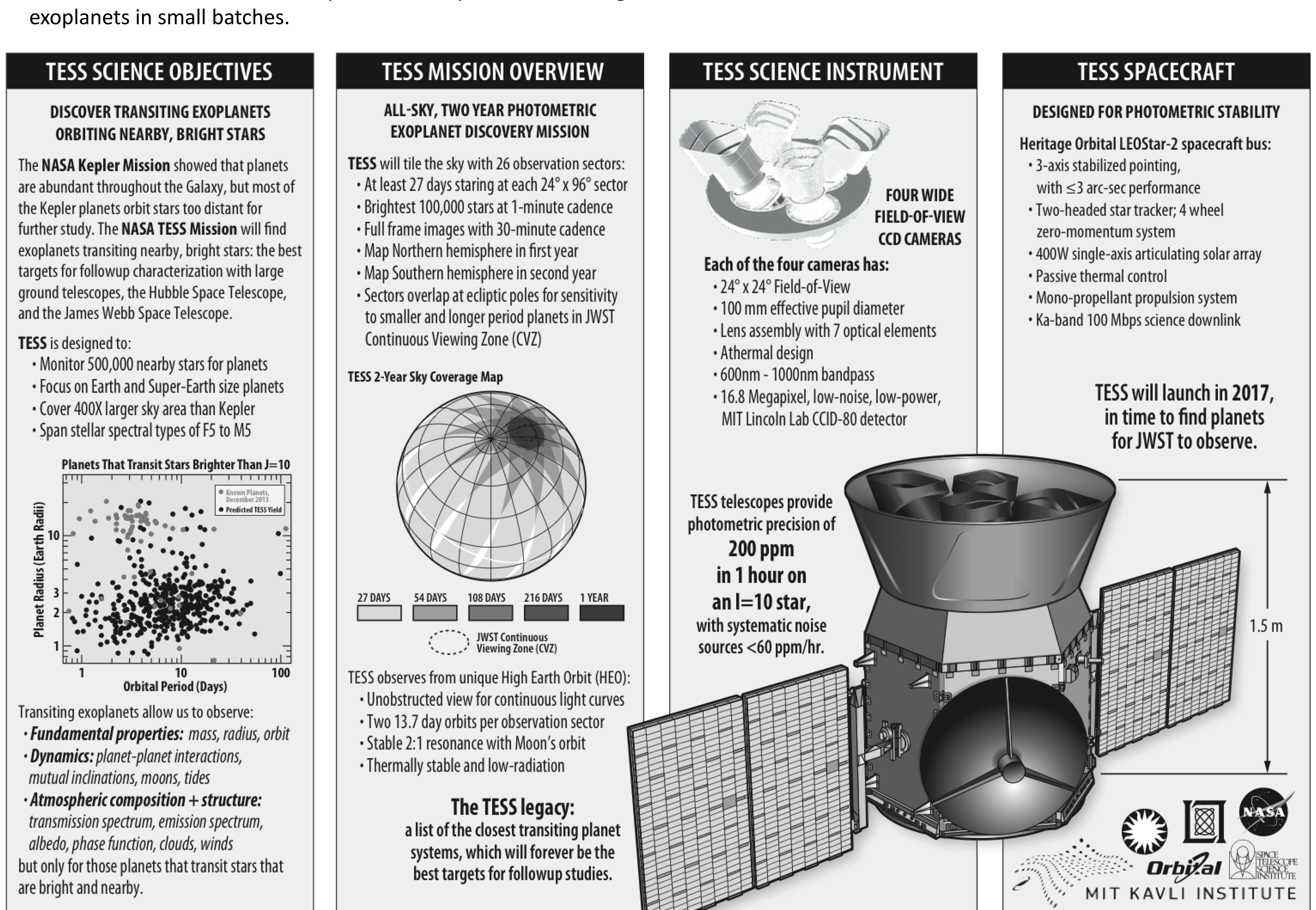
Figure 8: The Fomalhaut system. HST, NASA, and ESA.

Transit Timing Variations: By looking at little deviations in other methods, astronomers can determine if an exoplanet has a "partner" (another planet) tugging on it through gravity.

Pulsar Timing Method: Pulsars are hot, rapidly-spinning, dead stars. They are some of the most precise "clocks" in nature. When the rate at which they "tick" changes a certain way, it is evidence of a planet pulling on the pulsar through gravity.

Orbital Brightness Modulation: For large planets, astronomers can measure the starlight reflected by the planet itself.

Astrometry: Like the radial velocity method, but looking for the side-to-side wobble on the sky itself – hard, but doable!



2019 Nobel Prize in Physics

Half of the 2019 Nobel Prize in Physics went to Michel Mayor and Didier Queloz for discovering the first known exoplanet: 51 Pegasi b. Their pioneering work was the first step, and astronomers have now discover more than 4,000 additional planets in the years since!

The other half of the Prize went to James Peebles, for his detailed work in understanding the early universe. But that is a gigantic topic by itself!

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James Peebles
Prize share: 1/2

Ill. Niklas Elmehed. © Nobel Media.
Michel Mayor
Prize share: 1/4

Ill. Niklas Elmehed. © Nobel Media.
Didier Queloz
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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."

Images and synopsis from https://www.nobelprize.org/prizes/physics/2019/summary/

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