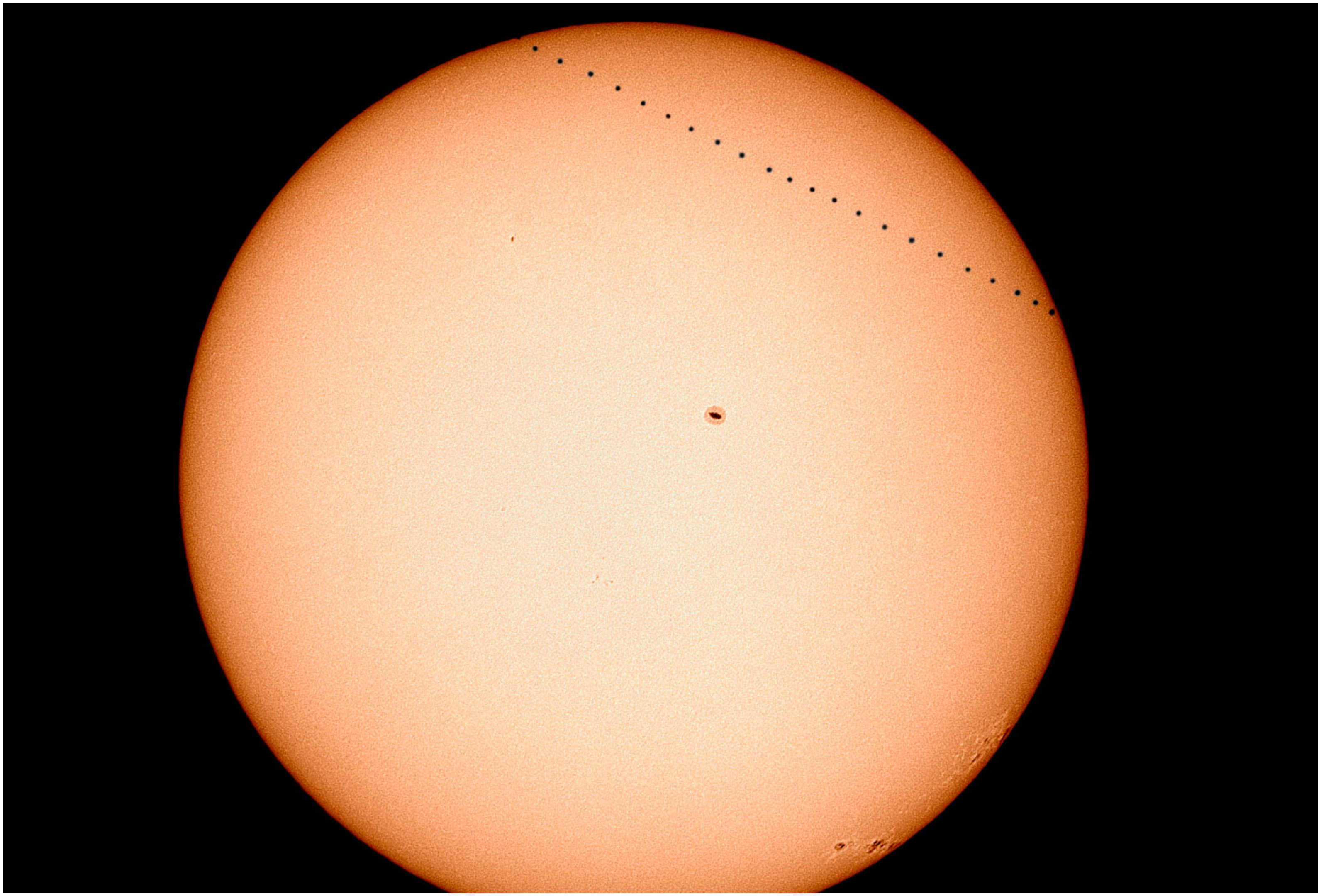
Transiting Planets

Lecture 4 of Planets Everywhere
Learners at Wind Crest, Feb 2020
Richard Edgar



A transit of Mercury, observed from the earth in 2016. Multiple images every 15 min. Another transit happened in 2019; next one 2032.

Now imagine viewing this from very far away.

- You can measure the total brightness of the sun.
- Mercury blocks a tiny fraction of the sunlight, given by the ratio of the area of the planet's disk to that of the sun.
- $\pi r_p^2 / \pi R_{sun}^2$ = (2425 km / 695,700 km)^2 = 12 parts per million (ppm).
- But Mercury is a small planet, and we know from the radial velocity method that there are Jupiter-mass planets very close to their stars.

- The star HD 209458 (its catalog number in the Henry Draper star catalog) is slightly more massive than the sun, slightly larger, and was known to have a planet with M_{min} = 0.6 Jupiter mass in a tight orbit.

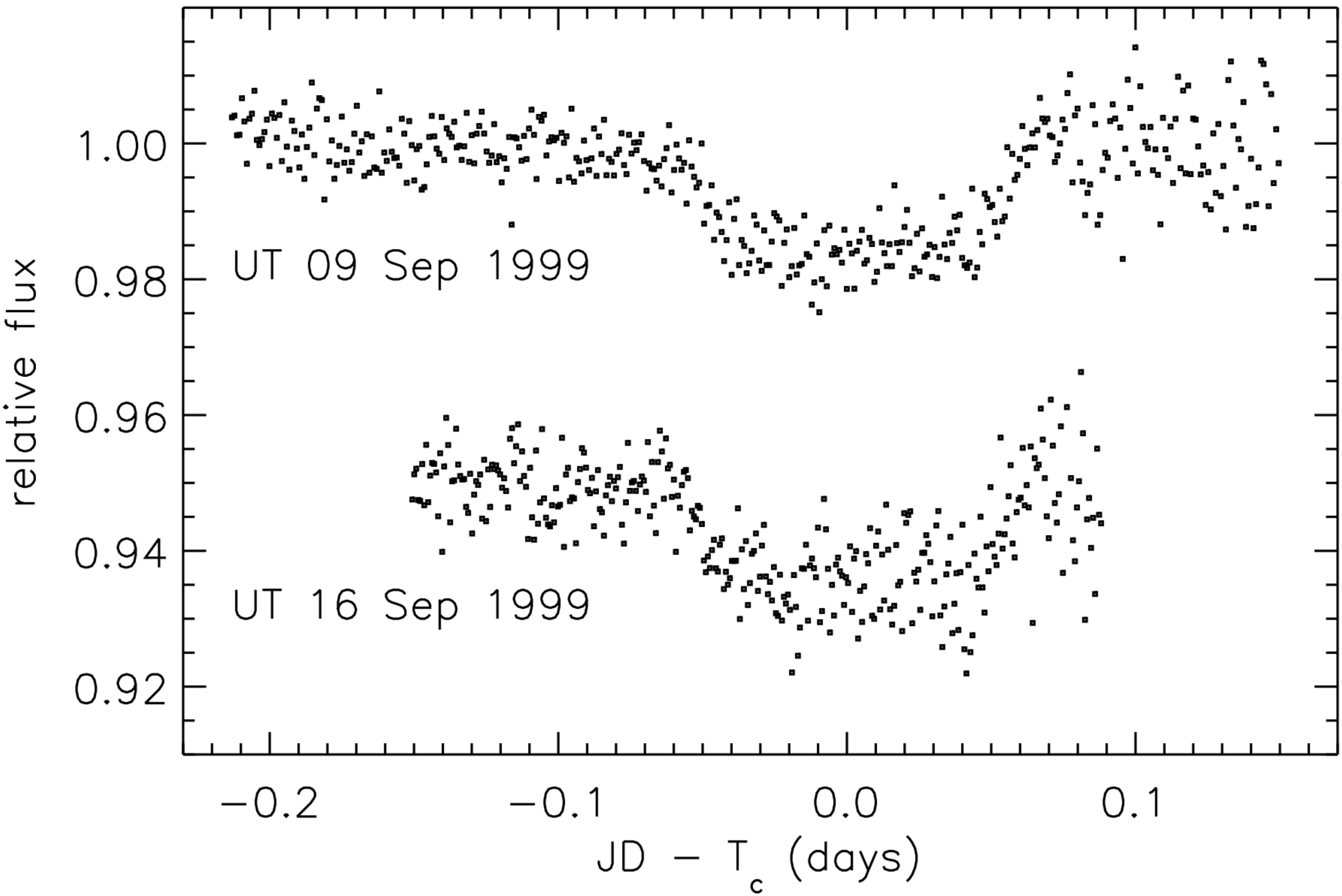
- Harvard astronomers (and others) undertook a search of many such systems with small ground-based telescopes and good cameras to watch for transits of those planets across their stars.

- On Sept 9 and 16, 1999 a 1.7% dip in the brightness of this star was observed. Astronomers from Tennessee saw half of a transit on Nov 8, 1999.

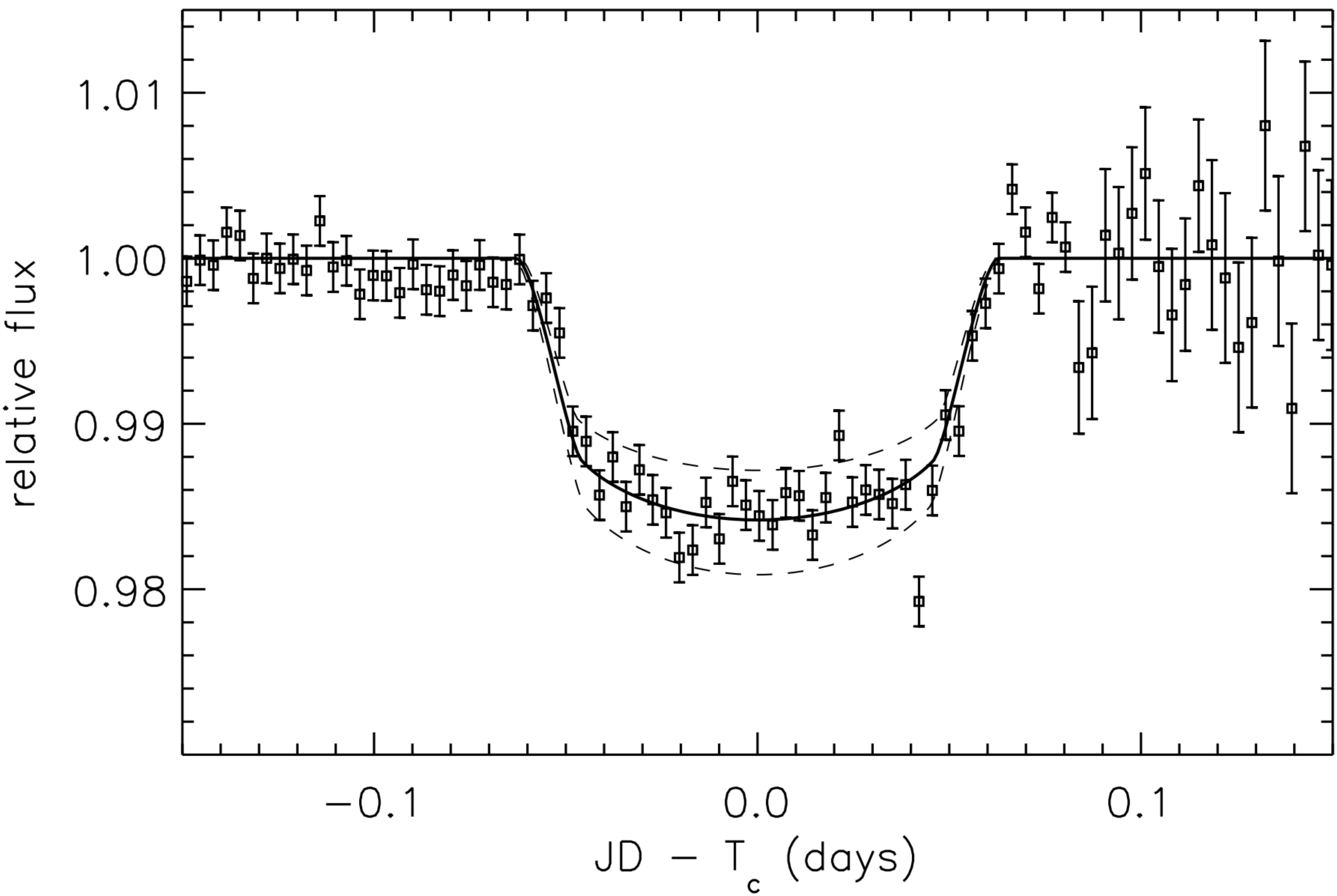
- The papers were published simultaneously.

- The transits last about 3 hours, and recur every orbit, 3.52 days.

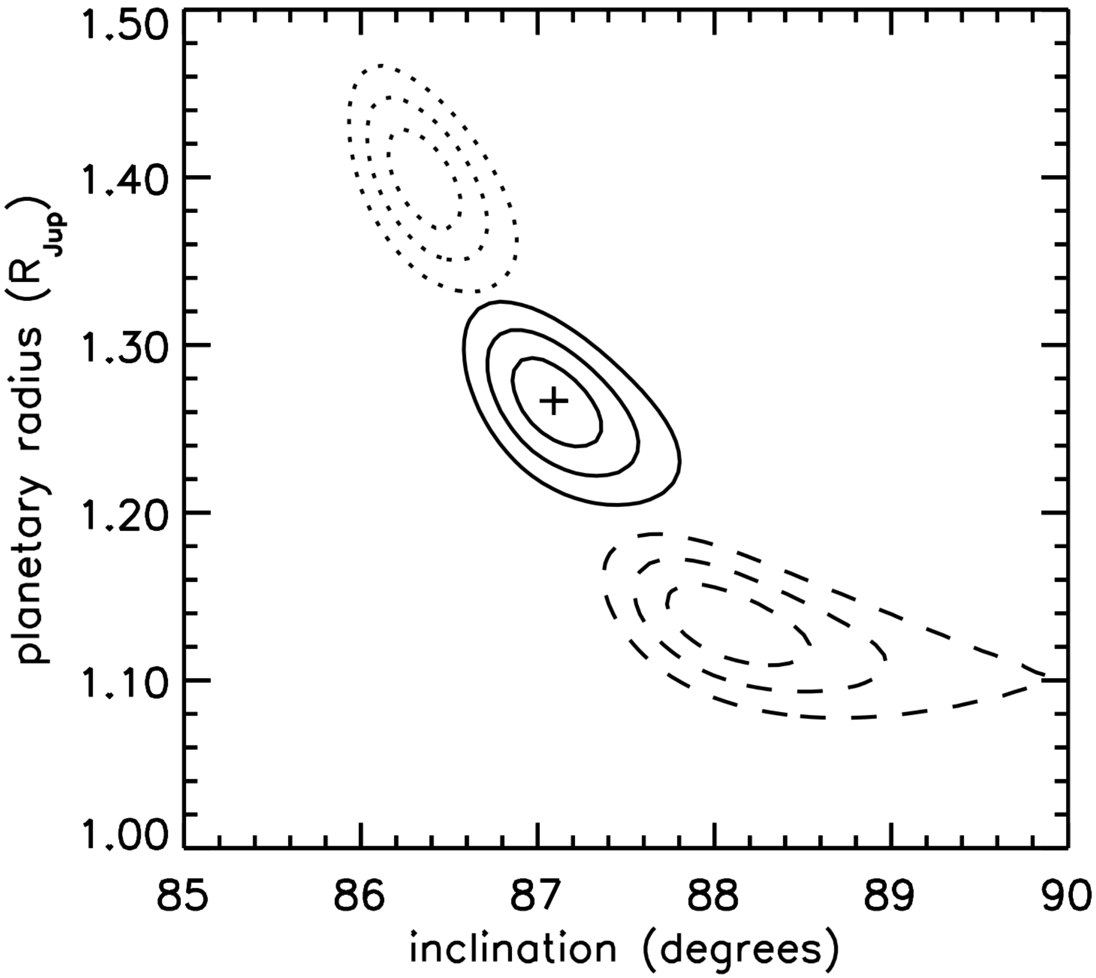
- This was part of David Charbonneau's PhD thesis. He's now on the faculty at Harvard.



relative flux
1.00
0.98
0.96
0.94
0.92
UT 09 Sep 1999
UT 16 Sep 1999
−0.2
−0.1
0.0
0.1
JD − T_c (days)



1.01
1.00
0.99
0.98
relative flux
−0.1
0.0
0.1
JD − T c (days)



Best fit planetary radius and inclination for 3 assumptions about the star (1.2, 1.1, 1.0 R_{sun})
"The dominant modeling uncertainty is that in the stellar radius."

Transiting exoplanets

- The method relies on the planet’s orbit being nearly edge-on (inclination about 90^{o}). The limits are related to the orbital radius vs. the stellar radius. Thus close-in planets are more likely to transit than far away ones.

- Unlike the radial velocity method, which relies on pointed observations with a fancy spectrograph, large parts of the sky can be watched with a small telescope and decent camera to see if any of them have planetary transits.

- …or other dips in brightness… What other events could be mistaken for planets?

- But before we leave HD 109458 b, let’s have a look around.

- Since we have both transits (which give us inclination and size of planet) and radial velocity (which gives us the mass), we can get a density, surface gravity, temperature, etc.

- They get $i = 87.1^{\circ}$, $m_p = 0.63\ M_{jup}$, $r_p = 1.27\ R_{jup}$, so it’s fluffier than Jupiter (due to stellar heating). T ~ 1400 K. Some H_2 is leaving the atmosphere.

- The planet is hot enough that the Spitzer Space Telescope could detect it directly in the infrared (by subtracting in-eclipse from out-of-eclipse brightness).

- Careful observations with a spectrograph, typically subtracting in-transit data from out-of-transit data, let us examine the spectrum of the planet’s atmosphere.

- Spectroscopy shows CO, H_2O, silicate dust grains, H_2, and other things in the atmosphere.

- This kind of observation suggests ways of detecting biosignature molecules in exoplanet atmospheres (i.e. you maybe don’t need life to be sentient to detect it.)

- Hubble observations confirm a very large hydrogen cloud centered on the planet, showing the atmosphere is escaping. This also provides insight into the planet’s magnetic field.

Interlude

- The 30th anniversary of the launch of the Hubble Space Telescope is coming up this spring. There's lots of cool stuff on https://hubblesite.org/hubble-30th-anniversary

- Including the following montage of images. Enjoy!

[redacted]

Transiting worlds: Backgrounds, biases, and false positives

- What can go wrong? Science is supposed to be a way of making sure you’re not fooling yourself (or anyone else).

- Binary stars… a glancing eclipse from another star
- low-mass stars and Brown Dwarfs (between planets and stars in mass) are only a little bigger than Jupiter, despite having 10 or 100 times the mass
- Uncertainties in the size of the host star
- Other stars that happen to be in the picture (binaries or chance alignments)
- Bias in favor of large planets close to the star
- Very nearly edge-on orbits required
- Starspots… can be nearly periodic because stars rotate.

- Need few-parts-per-million accuracy in the star brightness measurements.

- Weather is a problem for ground-based photometry

- You don’t need a big telescope! E.g. the “MEarth” program, searching for earth-like planets around nearby M stars (the little red ones) uses a network of automated 0.4 meter (16 inch) telescopes on the ground. https://www.cfa.harvard.edu/MEarth

- True planet detections should be very nearly periodic, like clockwork. Though multiple planets in the same system can interact and change the timing of transits.

Space telescopes for transiting planets

- Space telescopes can be very stable, and don’t care about the weather.

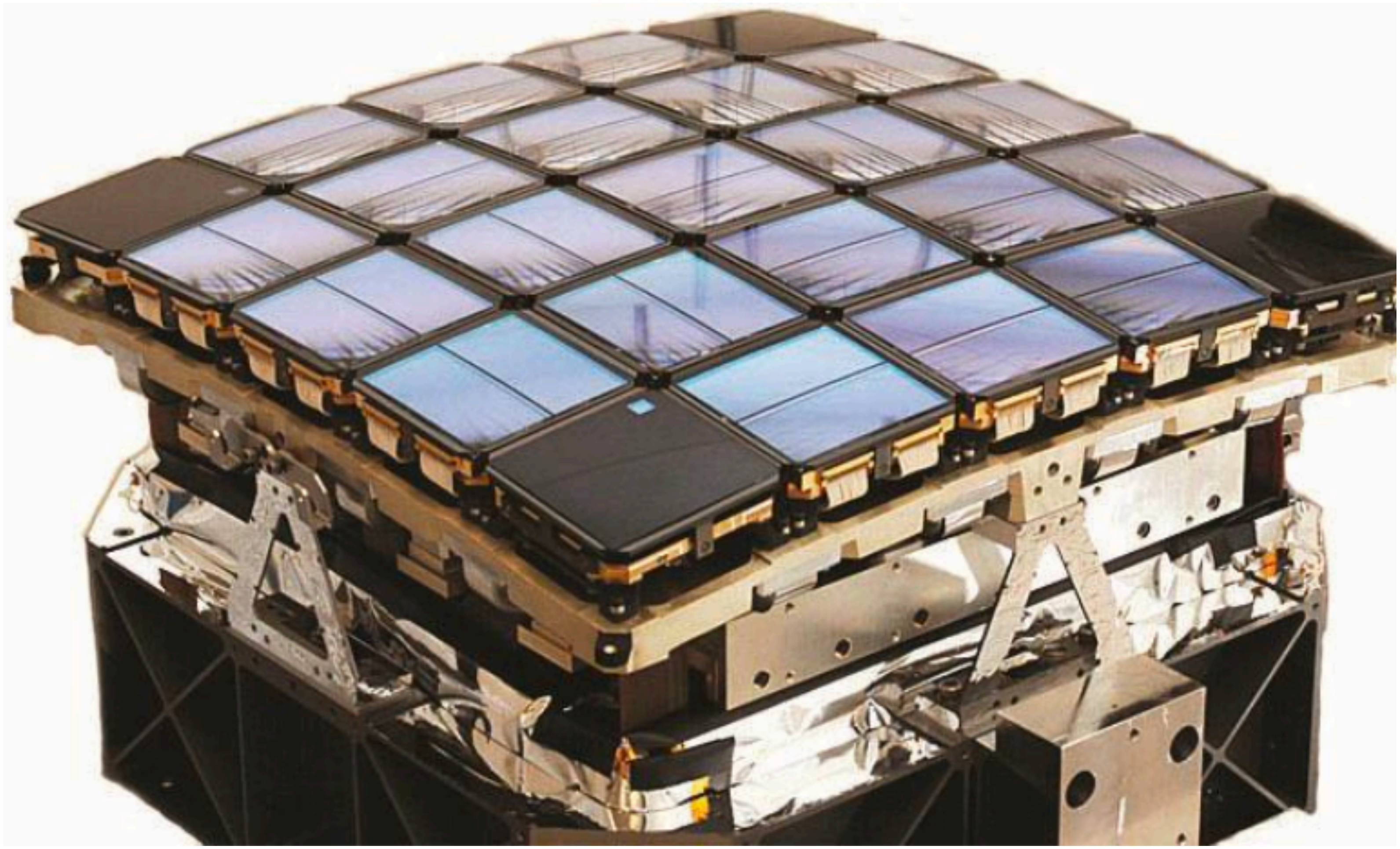
- ESA launched CoRoT (Convection, Rotation, and planetary transits) in 2006. It operated til 2013.

- Found a few dozen transiting planets, and learned a lot about stellar interiors.

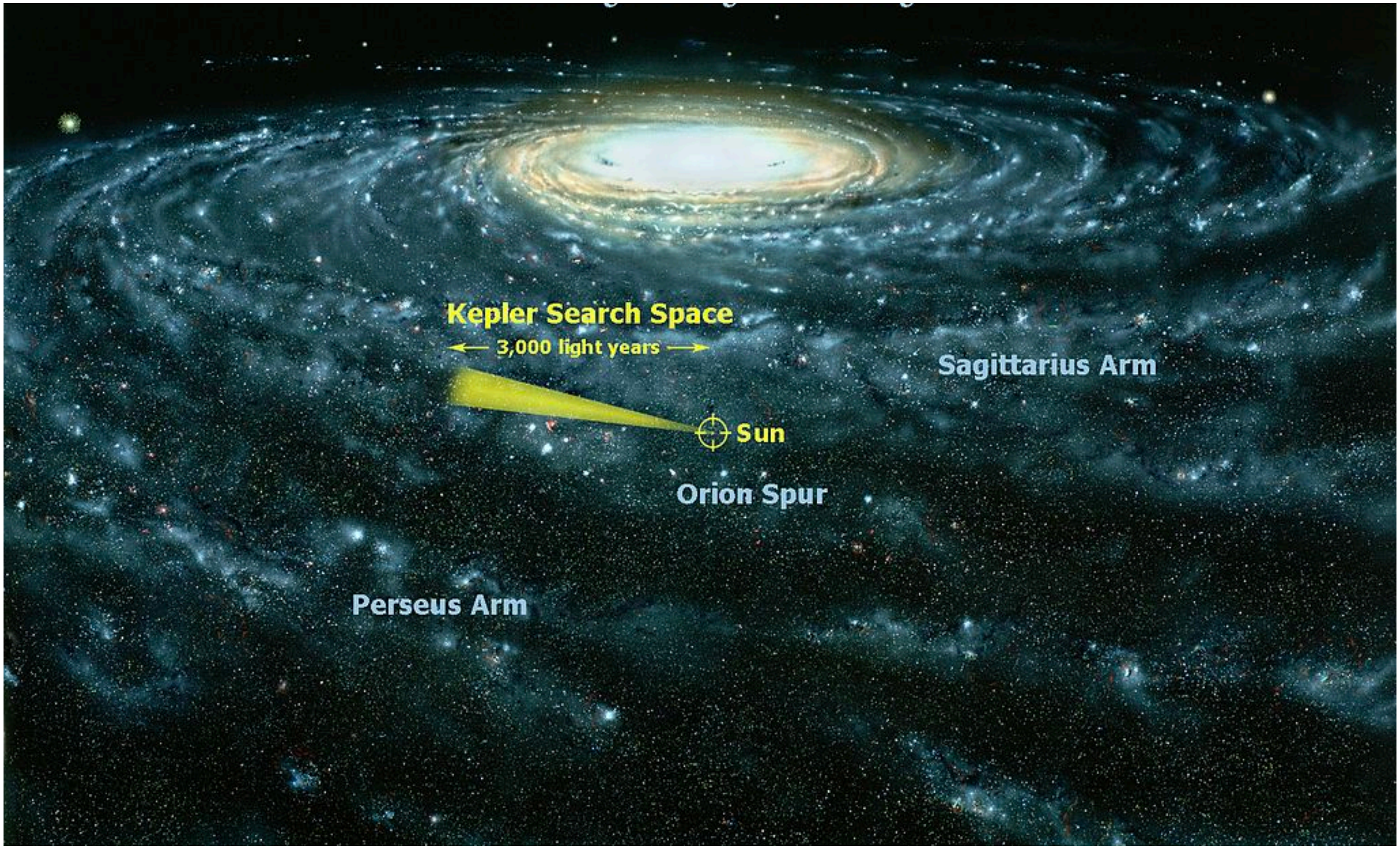
- It’s good to observe at least 3 transits to be sure they’re periodic, and get confirmation from ground telescopes.

The Kepler space telescope

- NASA project, built by Ball Aerospace in Boulder
- Carries an 0.9 meter Schmidt telescope
- Launched March 2009; started operations May 2009
- The objective was to stare at one field in the sky for years, hoping to detect all the earth-size planets around (sufficiently bright) sunlike (and smaller) stars in the field.
- Requires very stable pointing, and a large, stable, detector array.



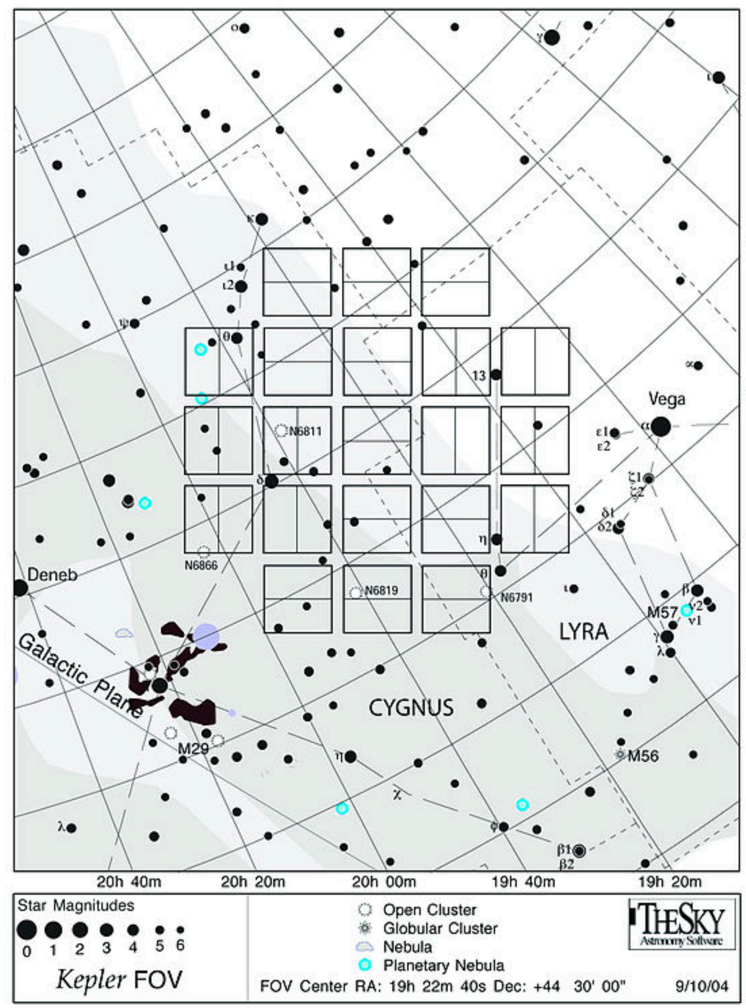
The Kepler detector array (curved to follow the telescope’s focal surface).



A panoramic view of the Milky Way galaxy with the sun in the foreground, showing the space searched by the Kepler main mission.

Kepler’s field of view

Kepler’s field of view, superimposed on a star map. It stared at a large area between Vega and Deneb, in the constellations Lyra and Cygnus. This is overhead in the summer sky.

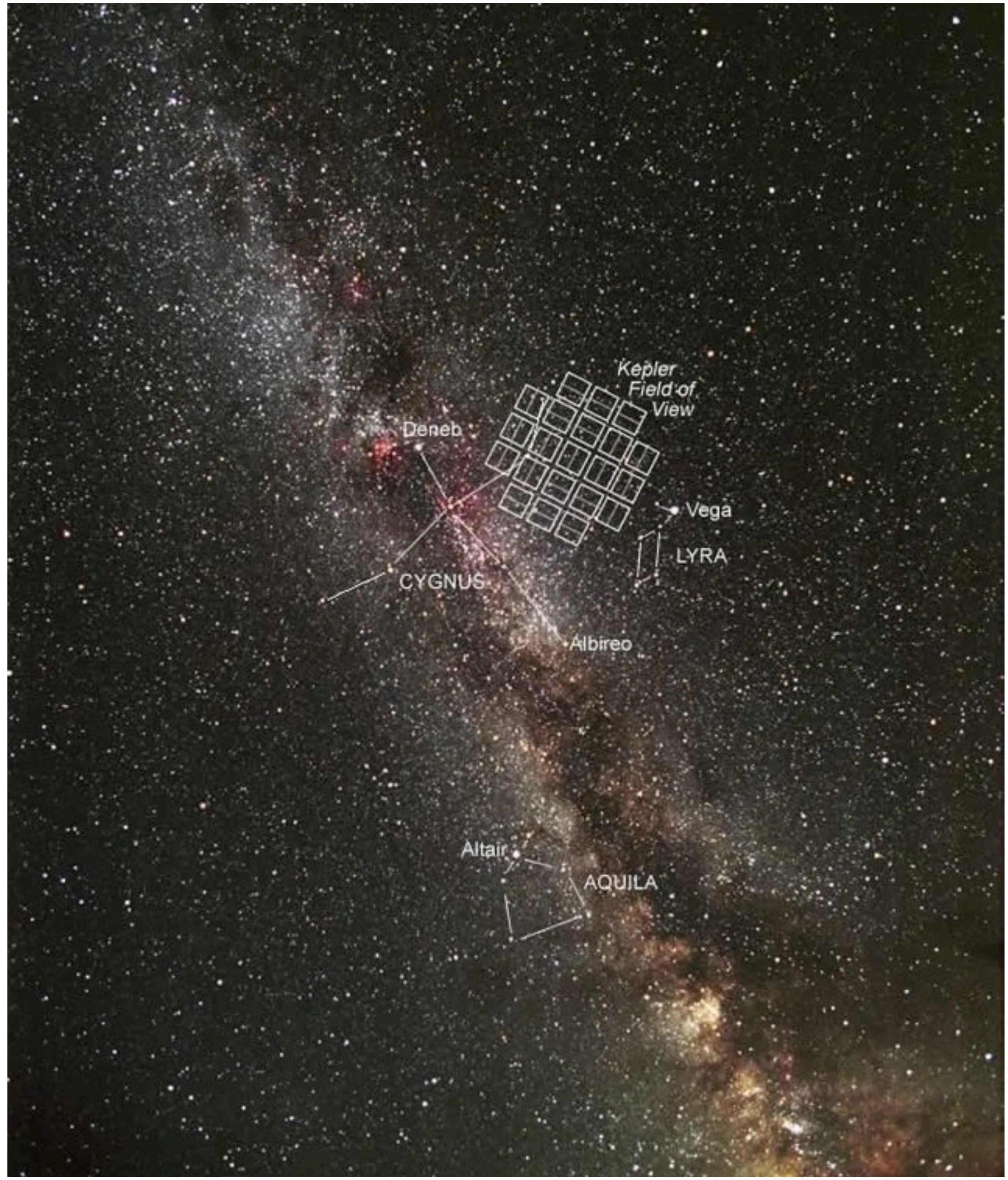


- The line of sight is near the Galactic plane, on one side of the “Summer Triangle” (Deneb, Vega, and Altair).

- It avoids the dust in the plane of the Galaxy, so stars as far away as 3000 light years can be studied.

- Strategy: take photos every 30 min for years.

- On-board processing reduces the data size (12 Gbytes/month).



- The field of view is 115 square degrees, or about 0.25% of the sky (“two scoops” of the Big Dipper).

- The primary mission lasted until 2013, about 4 years. An extended mission “K2” was possible after reaction wheel failures, but looking at different parts of the sky.

- The 4-year mission limits orbital periods to about a year, though one or two transits of longer-period planets were observed.

- As of Feb 25, 2020, there are 2295 confirmed Kepler planets in 1637 systems, of which 432 are multiple planet systems. (Overall transiting planets: 4187, 3105, 681)

- Kepler pixels are 2.5” on the sky, so ground-based followups verified no other star was in the same pixel as the candidate planetary system. A second star can make the transit dip look smaller than it should be.

- Radial velocity followup can in some cases get the masses of the transiting planets, and hence density, giving clues about the composition of the planets.

- Transit timing variations can give planet masses, and in some cases reveal non-transiting planets in the same system as transiting ones.

TESS, the Transiting Expolanet Survey Satellite

- Currently doing a near-all-sky survey for transiting planets around (mostly) nearby stars.
- Stares at a half-orange-slice piece of sky for a month and then moves on.
- Launched 2018. It’s working on year 2 of its 2-year primary mission.
- *Note to self: show the TESS overview webm here…*
  Link https://upload.wikimedia.org/wikipedia/commons/transcoded/4/45/NASA-Tess-SouthernSkyPanorama-20190718.webm/NASA-Tess-SouthernSkyPanorama-20190718.webm.480p.webm

- Short dwell times (around a month) mean short-period planets, which would include the habitable zone around cool M stars.

- The continuous viewing zone at the poles allows for finding longer-period planets. For example, TESS Object of Interest, TOI-700b, c, and d. (More in a bit…)

ESA's CHEOPS mission

- Characterizing ExOPlanets Satellite
- It'll do pointed observations of known transiting exoplanets. Most targets also have radial velocity measurements.
- Launched in Dec 2019. Starting its science mission.
- Yes, astronomers are inordinately fond of dumb acronyms. See DOOFAAS (the Dumb Or Overly Forced Astronomical Acronyms Site) https://www.cfa.harvard.edu/~gpetitpas/Links/Astroacro.html

Other stuff to do with transit data

- Watch the planet as it revolves around its star. If it goes behind (“secondary transit”), the system is slightly fainter (works especially well for hot jupiters in the infrared). Crude maps can be made… Algorithms for this can be checked against the moons of Jupiter

- Spectra taken at different orbital phases… The velocity of the planet should move opposite to that of the star, and by much larger amounts (due to the Döppler effect).

- Look for interesting gases in the spectrum (e.g. O_2, CH_4, CO_2, others)

- The oxygen in the earth's atmosphere is biogenic: it's a by-product of photosynthesis. It's not very stable, and would react with other things, fading over time if not replenished.

- But it's possible to have lots of oxygen without life as well…

- Imagine a planet like early Venus where the greenhouse effect runs away, the oceans boil, and there's lots of water vapor in the atmosphere.

- Ultraviolet from the star can break up water molecules, leaving O_2 and H_2, and the H_2 can, in time, escape or combine with other things to form, e.g. CH_4 or NH_3.

Next time…

- We’ll talk about a few interesting planetary systems
- Statistics of the 4000+ planets in the databases (but mind the biases of the various detection techniques!)
- Young planetary systems and proto-planetary disks
- Other detection methods