Brown dwarfs, exoplanets & ‘exo’-tic objects

Jan Budaj
Astronomical Institute
05960 Tatranska Lomnica
Slovak Republic

SPACE::TALK, Dec 5, 2019, Kosice

form: slides in English with presentation in Slovak

Supported by the grants: VEGA 2/0031/18, APVV 15-0458, and ERASMUS+(Per Aspera ad Astra Simul).

Content

- Basic definitions
- Basic BD EGP properties
- Atmospheres
- History
- Methods of detection
- Transits, occultations & ...
- Disintegrating exoplanets
- Exoasteoids
- Exocomets
- Some ‘exo-tic’ systems

Definitions

Basic facts:

- Stars on MS are burning hydrogen
- Hydrogen burning limit is 75 M_J
- Deuterium burning limit is 13 M_J, it is analogous to the H burning limit
- Companions with masses 0.1-0.01 Msun missing = brown dwarf desert
- There may be a natural distinction between object formed from the proto-planetary disc and those from the fragmentation but it is difficult to distinguish the formation scenario by the observations
- Radial velocity method can determine only msini

Brown Dwarf is:

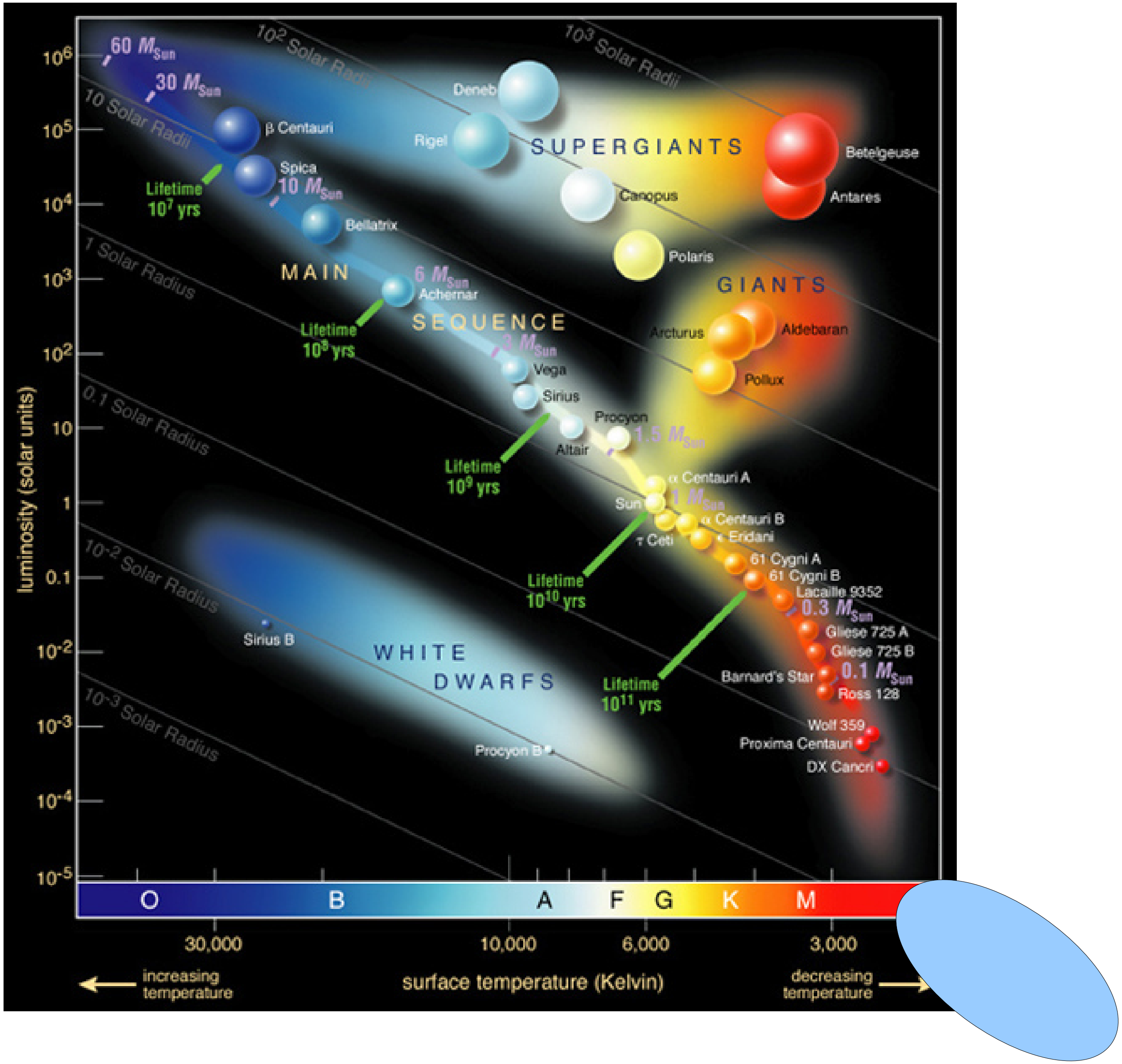
- Not a star nor a planet
- Does not burn H but burns deuterium
- Object with mass $75>M>13\ M_J$

Exoplanet is:

- Object orbiting a star other than the Sun or stellar remnant (no free floating planets)
- Does not burn H nor deuterium
- There is no precise definition but most researchers accept an object with $m<13$ or $m\sin i<13M_J$
- This definition is not final and it will change
- BDs & exoplanets are collectively called sub-stellar objects

Where do brown dwarfs live?

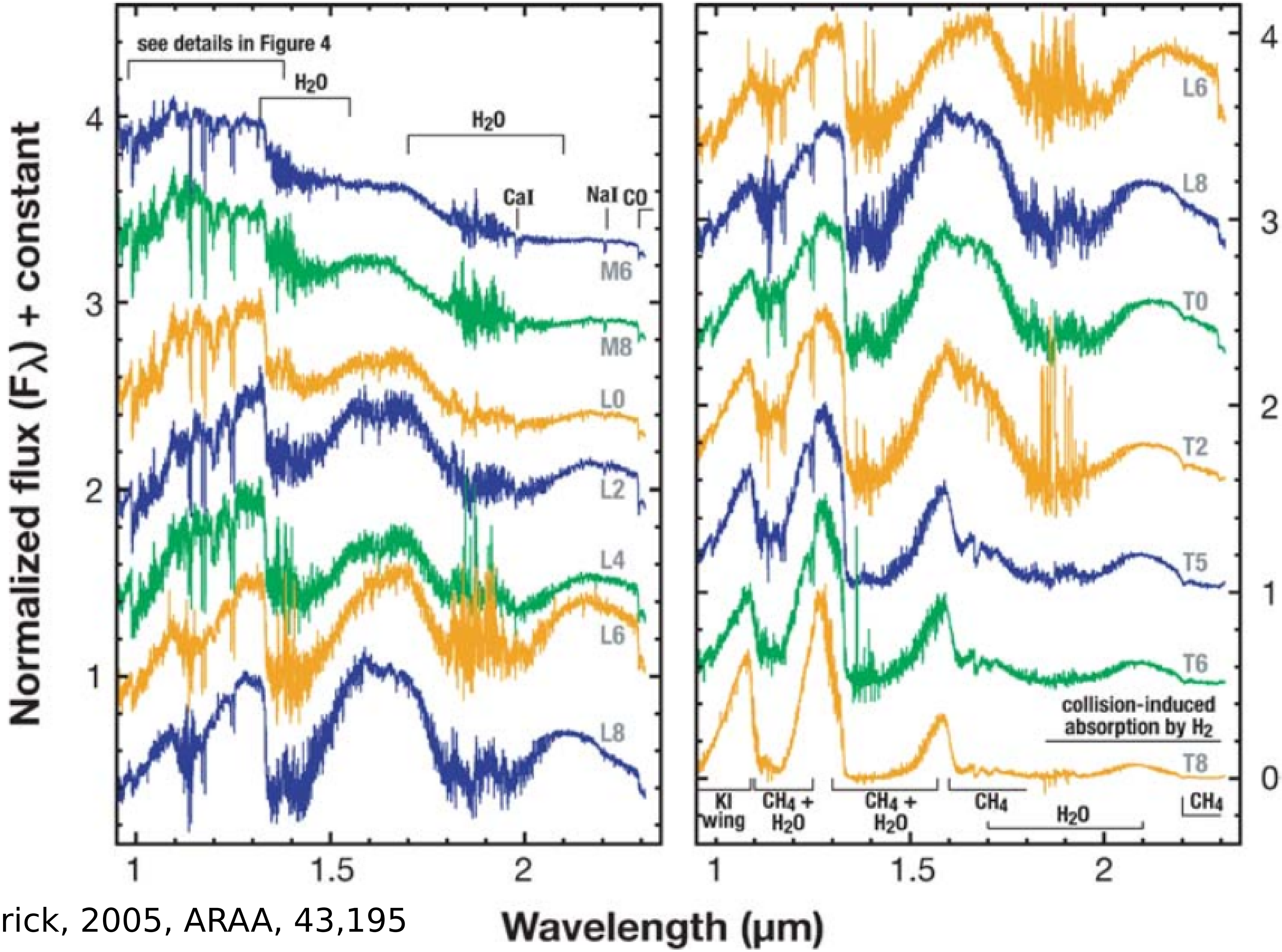
Where do Brown dwarfs live?



Brown dwarfs: definition

- They are cold, sp. types L-T-Y, 2300-200 C (20? C).
- But: Brown dwarfs and LTY dwarfs are two different things.
- LTY dwarfs are continuation of dwarfs (hot,yellow,orange,red…) based on the spectral classification.

L-T Spectral classification



Kirkpatrick, 2005, ARAA, 43,195

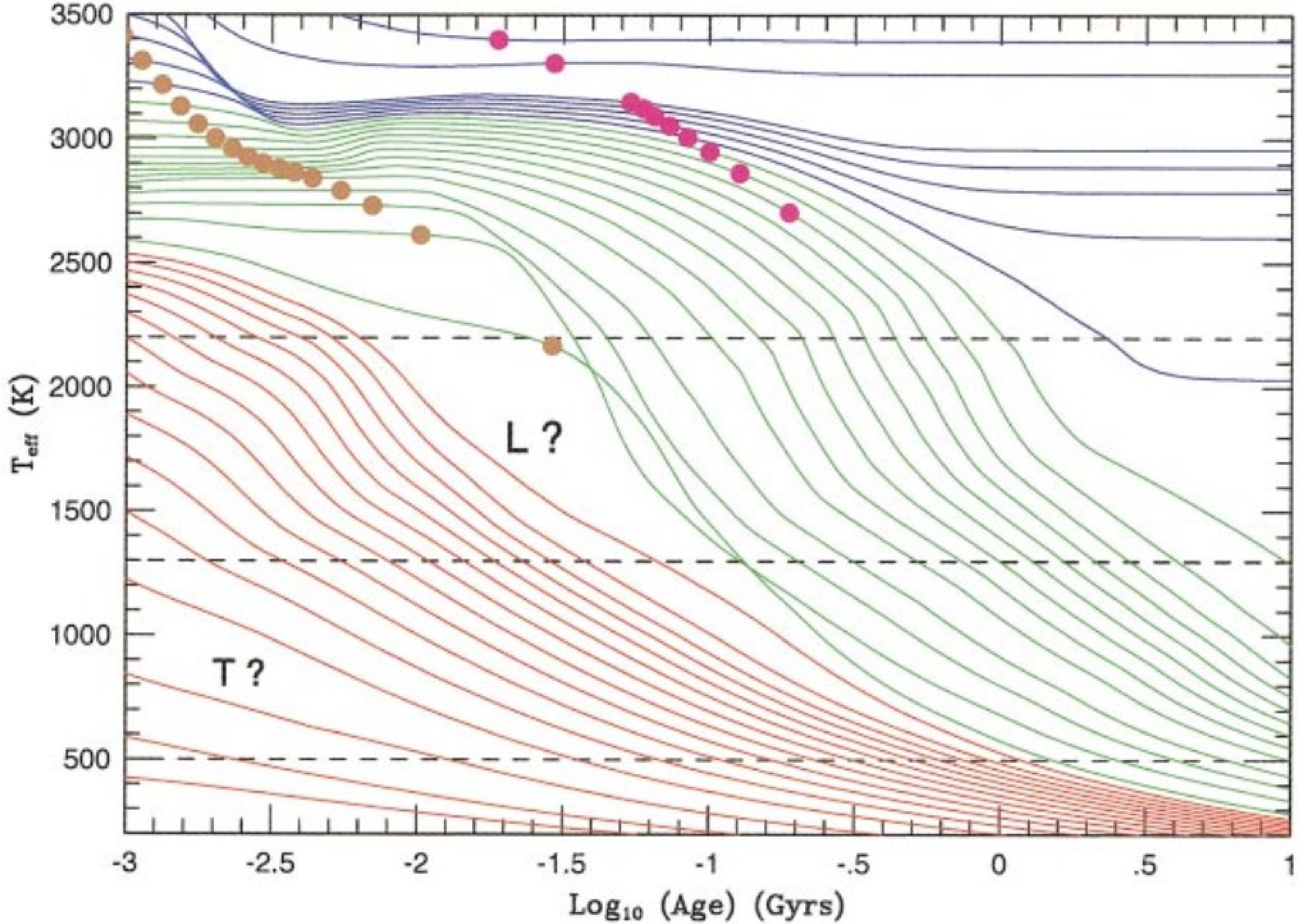
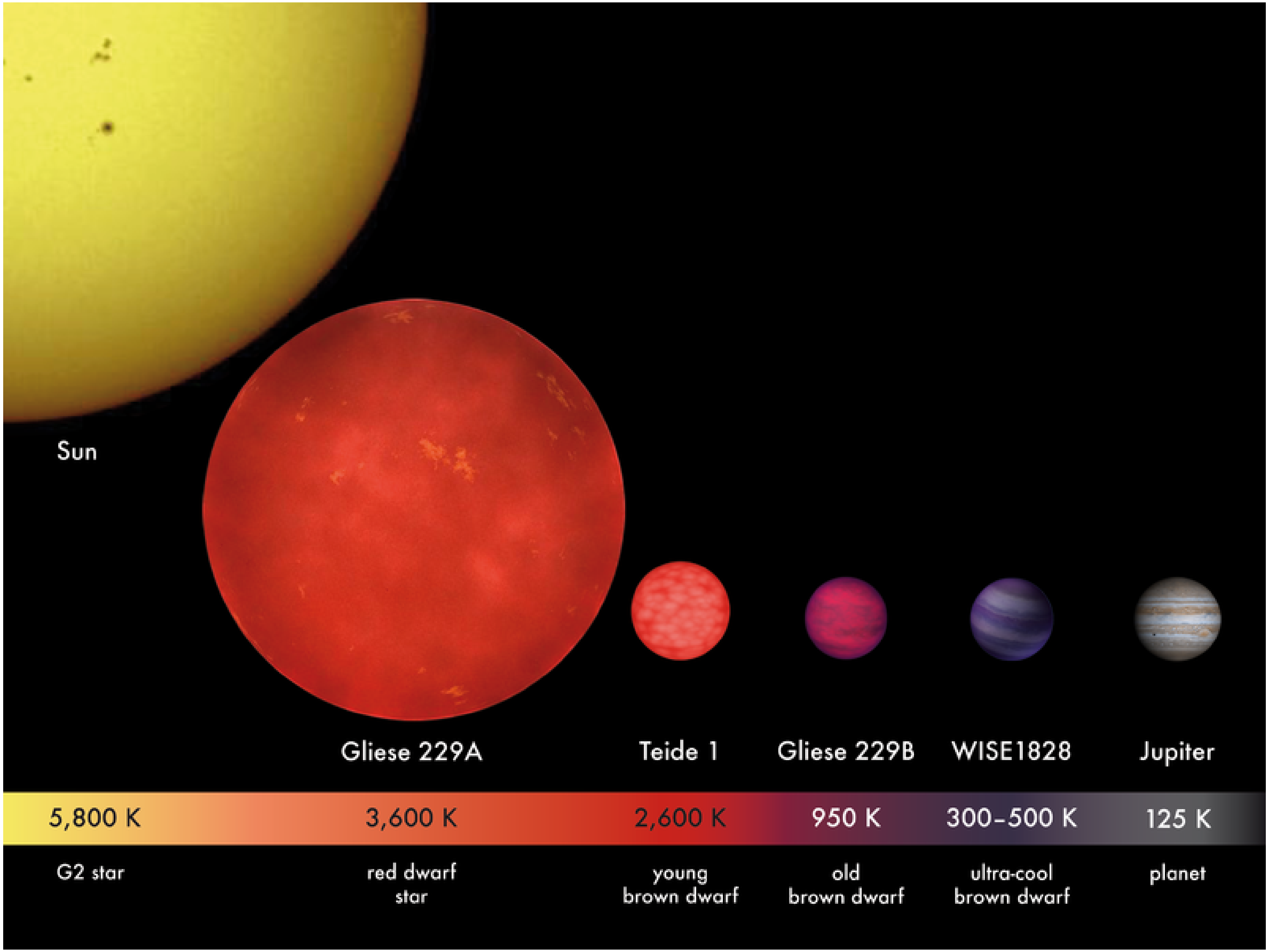


FIG. 8. This figure depicts the evolution of T_{eff} (in K) with age for the mass set used in Fig. 1 and with the same color scheme. Superposed are dots which mark the ages for a given mass at which 50% of the deuterium (gold) and lithium (magenta) are burned. Though the L and T dwarf regions are as yet poorly determined and are no doubt functions not only of T_{eff}, but of gravity and composition, approximate realms for the L and T dwarfs are indicated with the dashed horizontal lines. The spectral type M borders spectral type L on the high-temperature side. Note that the edge of the hydrogen-burning main sequence is an L dwarf and that almost all brown dwarfs evolve from M to L to T spectral types [Color].

Burrows et al. 1997

Brown dwarfs



Young planets in protoplanetary disk

Angular momentum transport:
radial (viscosity) or vertical (centrifug.)

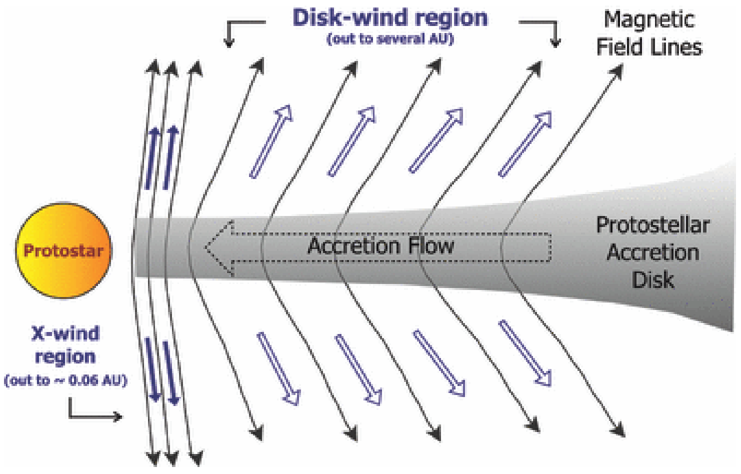
↓

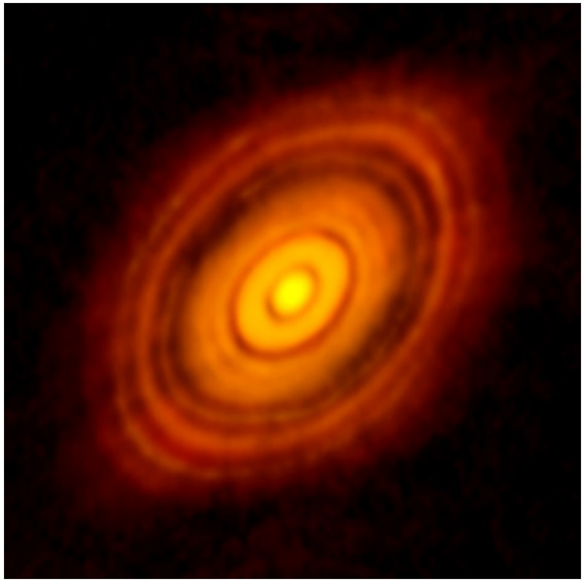
Matter transport: accretion, jets

↓

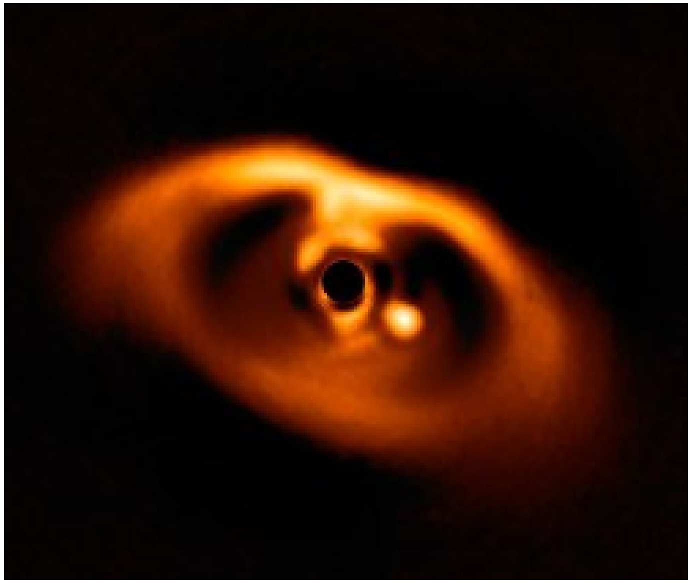
Planet migration

Vertical transport via winds accelerated centrifugally (Salmeron & Ireland 2012):





HL Tau as observed by ALMA (Brogan et al.2015)



Birth of a planet in the disk of PDS 70
(Muller et al. 2018, VLT)
Coronograph, 20AU, 1000C,

Atmospheres

What is an atmosphere?

Atmosphere is a region which shapes the emergent spectrum, region from where the photons escape the object and regions that affect the above.

Relevant processes: irradiation, scattering, heating, day-night side heat transport, convection, dust formation, clouds, rain-out...

Dust, Clouds, Rain-out

Dust is a condensate, solid or liquid.
Grain is a solid grain or a droplet.
Cloud is an ensemble of grains not only in the atmosphere (in the interplanetary, interstellar space…).
Rain-out is displacement of grains and chemicals due to rain.

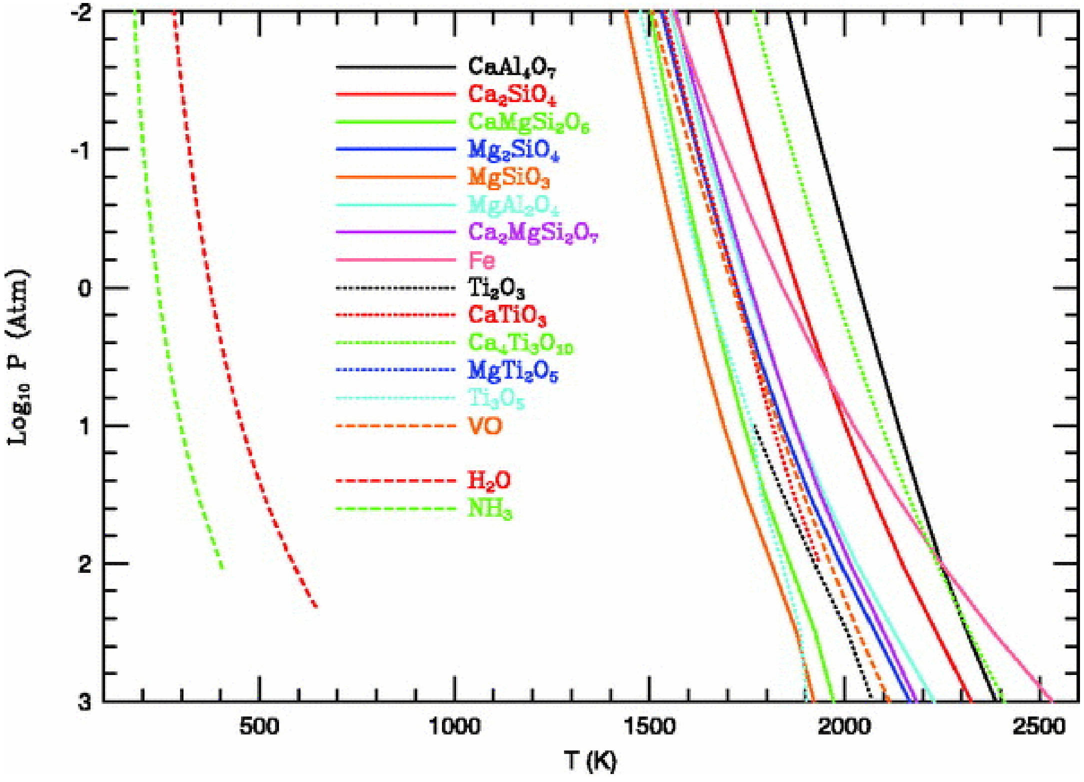
Most refractory species:
composed of Ca, Al, Ti, Mg, Si
CaAl4O7-grossite, Al2O3-corundum, Mg2SiO4-forsterite, MgSiO3 enstatite

Alkali metals: Na,K,Li

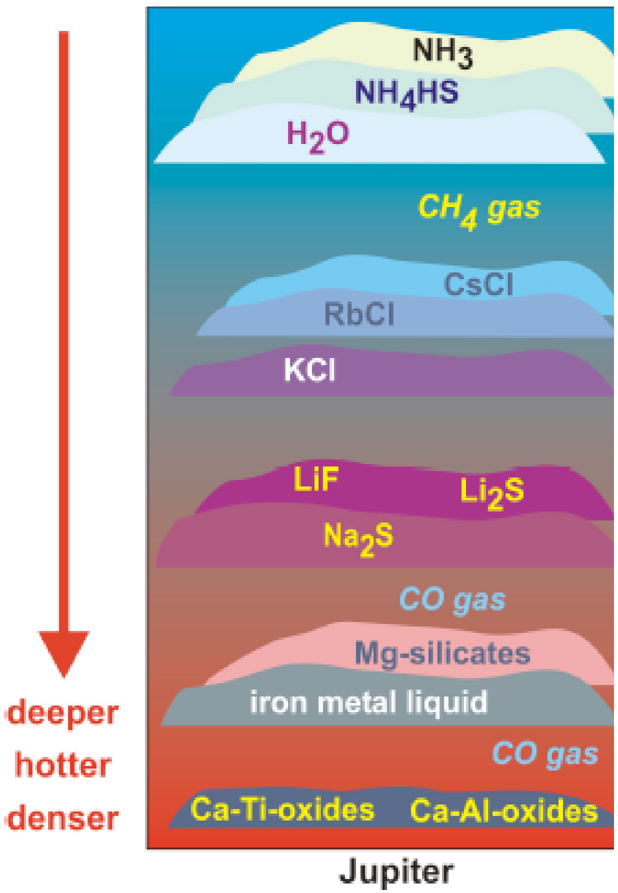
Volatiles:
H2O, NH3

Proof of rain-out: the detection of H2S in Jupiter. Sulfur is not refractory. It should have been in the form of FeS. However, Fe is refractory, it rained out, FeS could not form hence H2S is observed.

Solar metallicity condensation curves taken from Burrows et al. 2006, ApJ, 640, 1063



Cloud structure



Lodders & Fegley (2006)

A brief history of exoplanets

First extrasolar planet discovery (2 planets orbiting a pulsar PSRB1257+12):
Wolszczan & Frail, 1992,Nature, 355,145

First exoplanet around a MS star – 51 Peg:
Mayor & Queloz, 1995, Nature, 378, 355

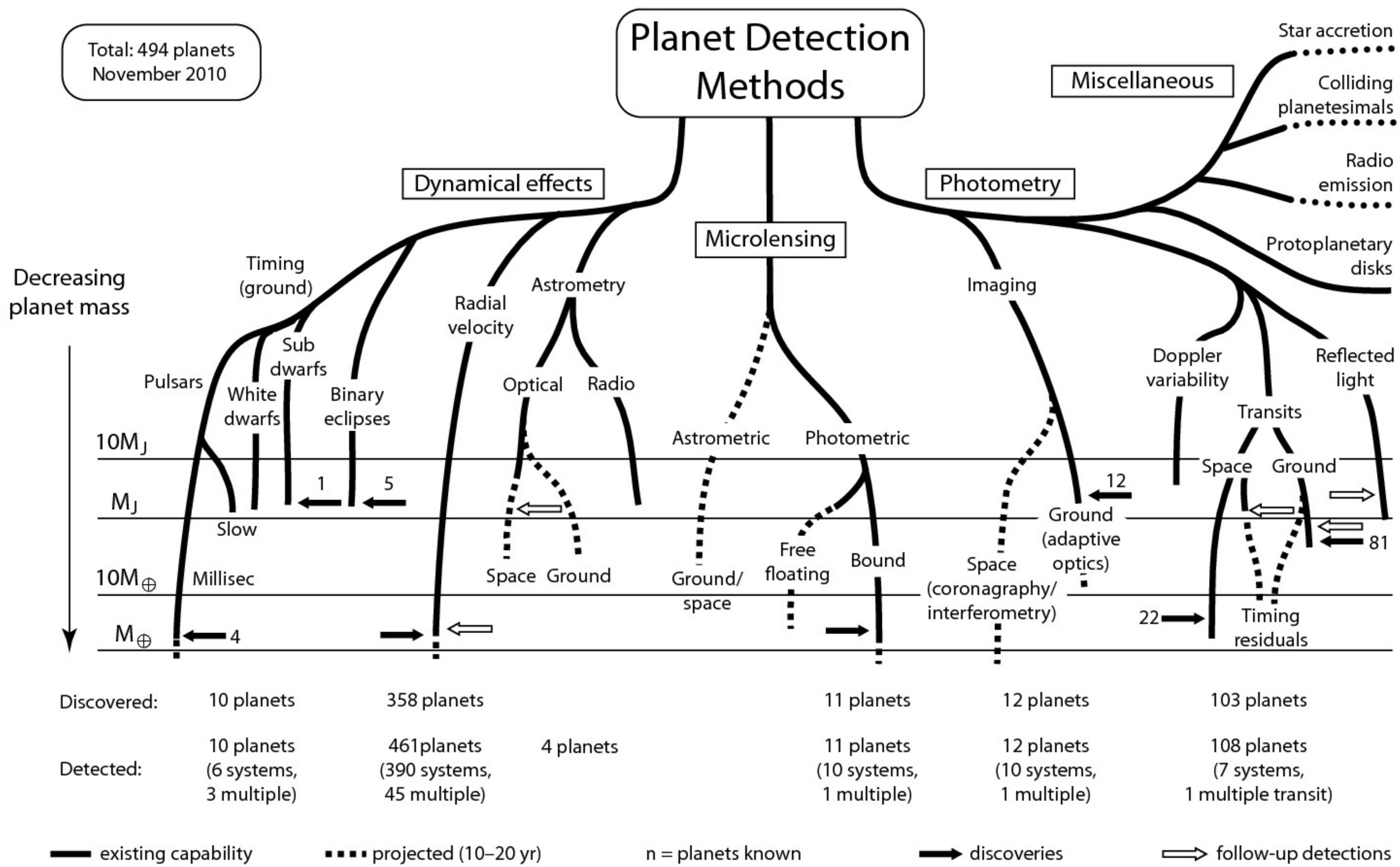
First bona fide brown dwarf Gl229B, a companion to M1 dwarf Gl229, became a prototype of T dwarfs:
Nakajima et al. 1995

First transiting exoplanet - HD 209458b:
Henry, Marcy, Butler, Vogt, 2000, ApJ 529, L41
Charbonneau, Brown, Latham, Mayor, 2000, ApJ 529, L45

Two Earth-sized transiting planets (orbiting Kepler 20):
Fressin et al. 2012, Nature, 482, 195
A 2.4 Re planet in the habitable zone of a Sun-like star (Kepler-22b):
Borucki et al. 2012, ApJ, 745, 1208

as of Oct 24, 2019: 4122 exoplanets (2962 transiting, 862 rad.vel., 131 imaging, 101 microlensing)

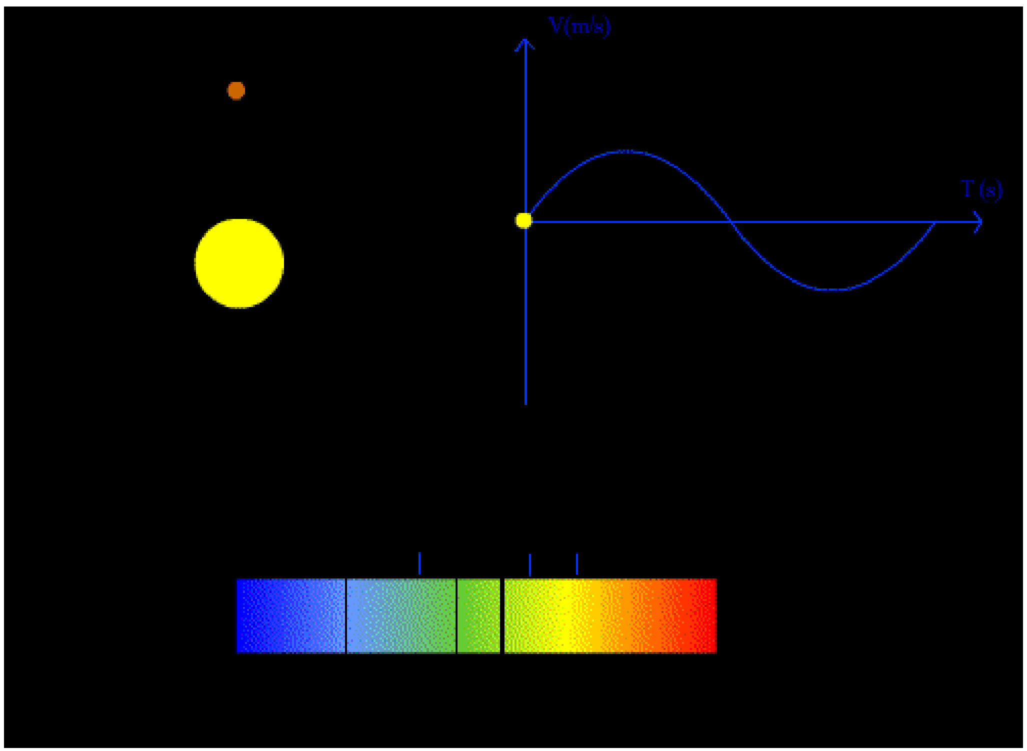
Corot, Kepler, TESS

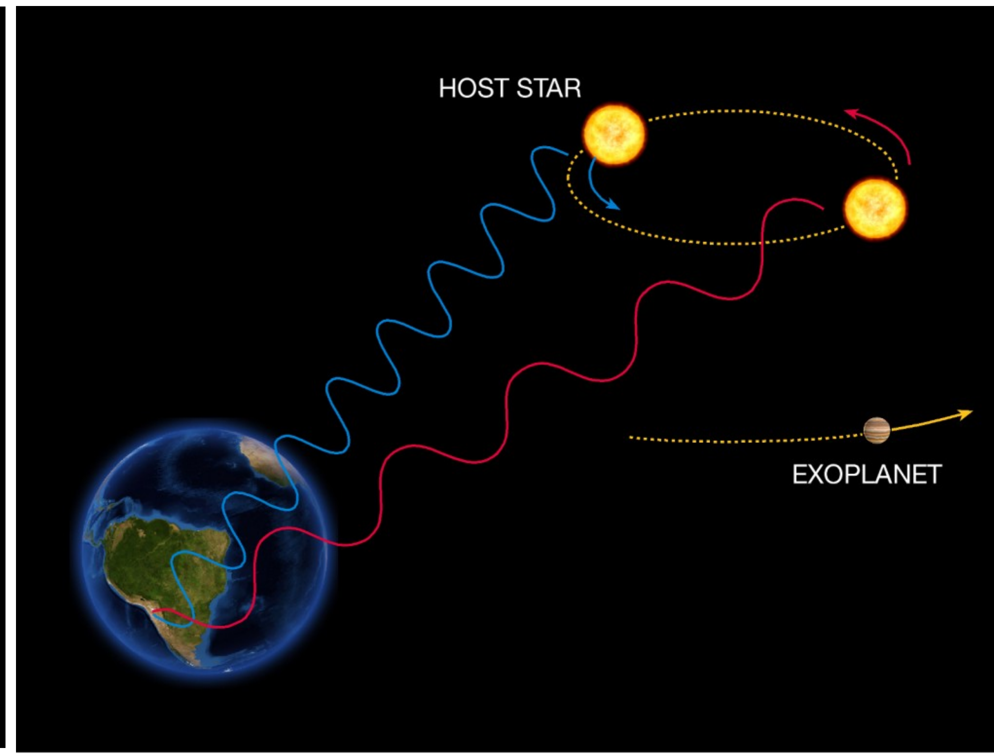


Total: 494 planets
November 2010
Planet Detection Methods
Miscellaneous
Star accretion
Colliding planetesimals
Radio emission
Protoplanetary disks
Dynamical effects
Microlensing
Photometry
Decreasing planet mass
Timing (ground)
Pulsars
White dwarfs
Sub dwarfs
Binary eclipses
Radial velocity
Astrometry
Optical
Radio
Astrometric
Photometric
Imaging
Doppler variability
Transits
Reflected light
10M_J
M_J
10M_⊕
M_⊕
Slow
Millisec
1
5
4
Space
Ground
Ground/ space
Free floating
Bound
Space (coronagraphy/ interferometry)
Ground (adaptive optics)
12
Space
Ground
81
22
Timing residuals
Discovered:
10 planets
358 planets
11 planets
12 planets
103 planets
Detected:
10 planets (6 systems, 3 multiple)
461planets (390 systems, 45 multiple)
4 planets
11 planets (10 systems, 1 multiple)
12 planets (10 systems, 1 multiple)
108 planets (7 systems, 1 multiple transit)
existing capability
projected (10–20 yr)
n = planets known
discoveries
follow-up detections

Radial velocity variation

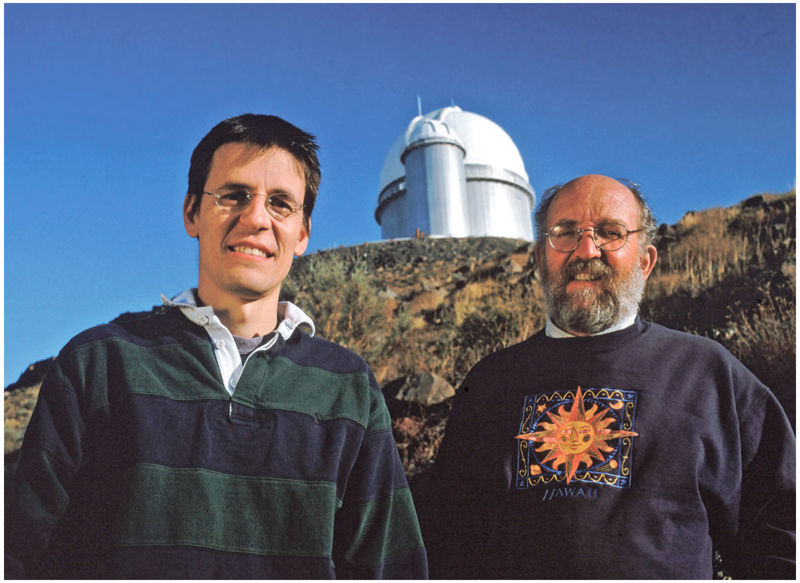
Planet is not visible. We observe the spectrum and movement of the star.
Can determine some orbital elements and msini. m vs i degeneracy.





The Radial Velocity Method

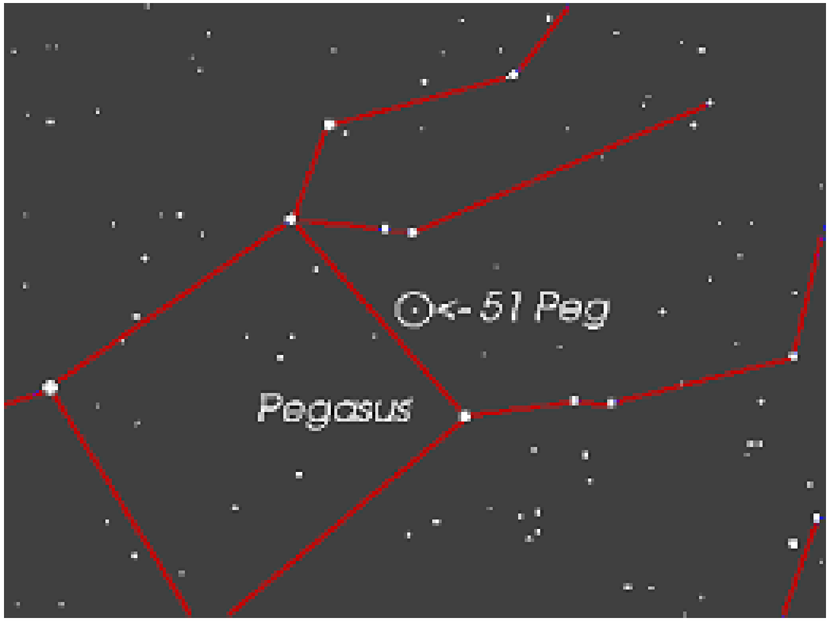
ESO Press Photo 22e/07 (25 April 2007)

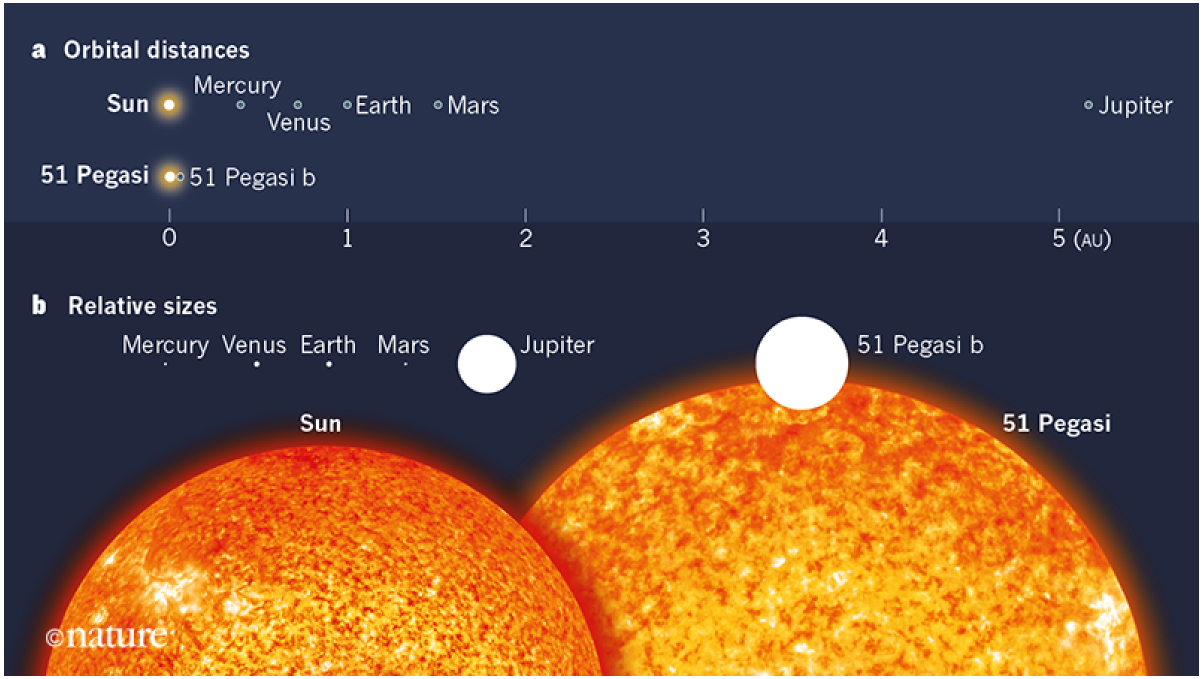


Nobel prize 2019

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 jointly to Michel Mayor and Didier Queloz "for the discovery of an exoplanet orbiting a solar-type star."

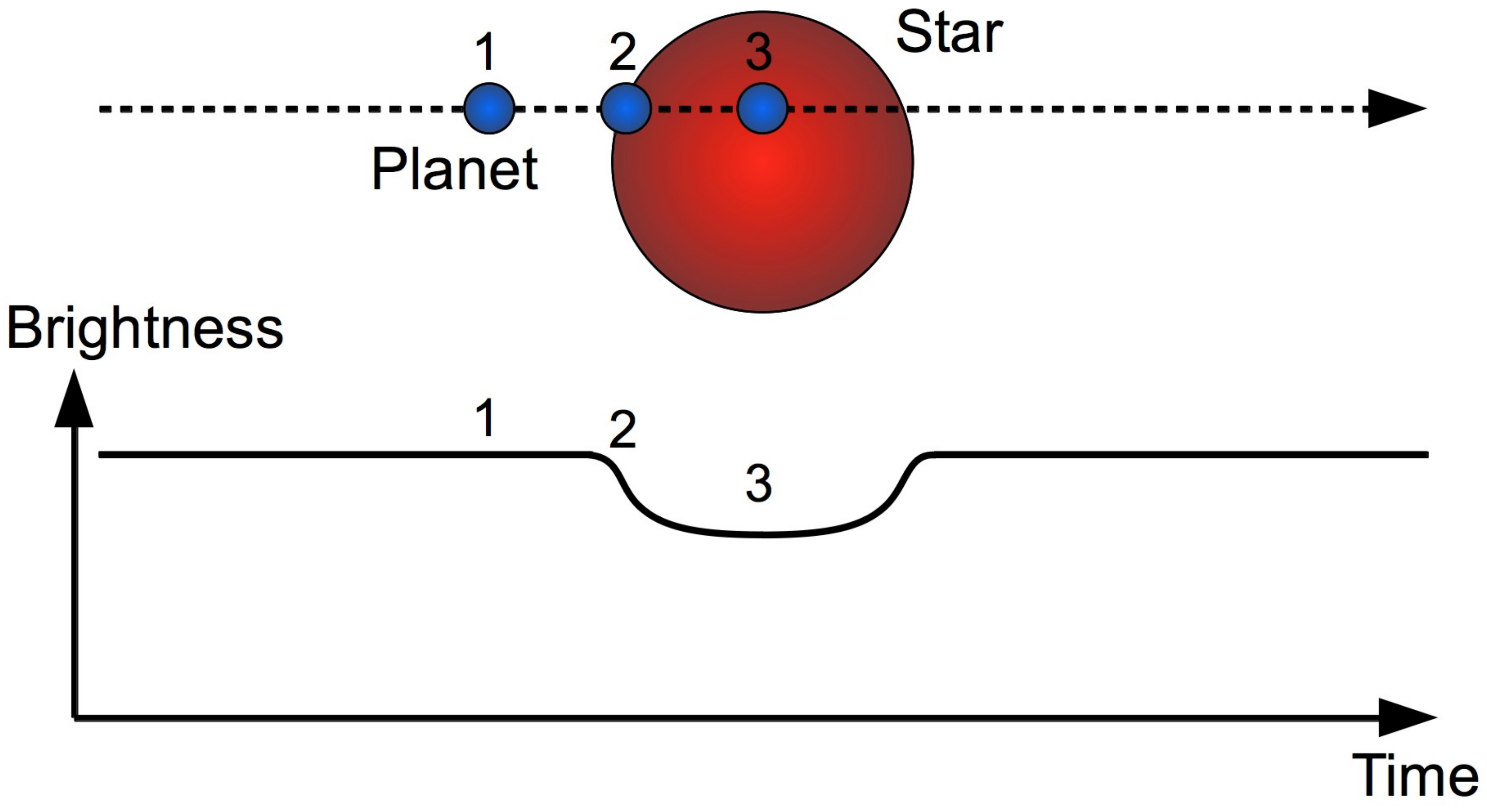
visited Slovakia in 2011



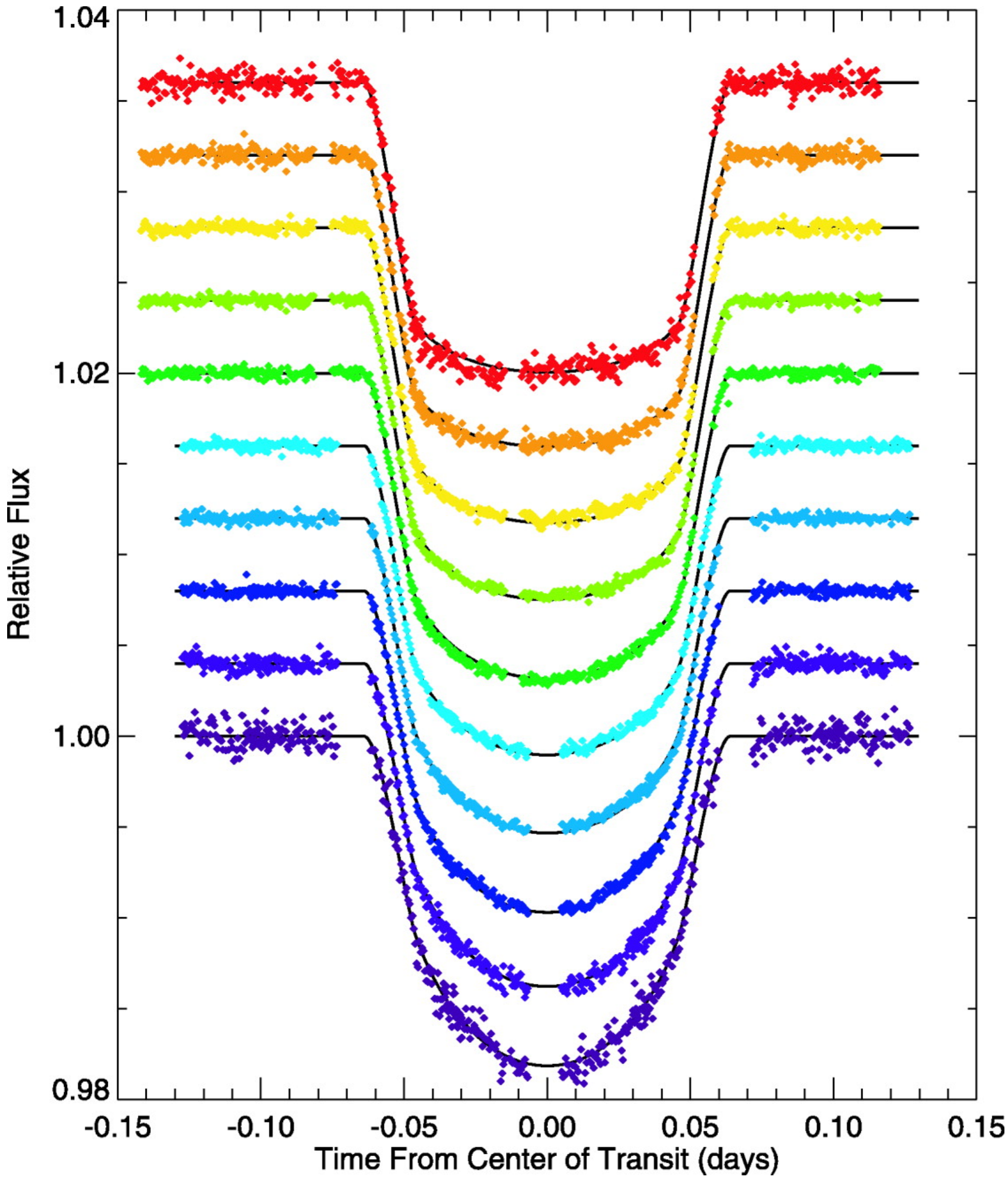


Transit of the planet

Occultation (secondary eclipse) – planet is behind the star.
Can determine some orbital elements +i+Rp/Rstar.



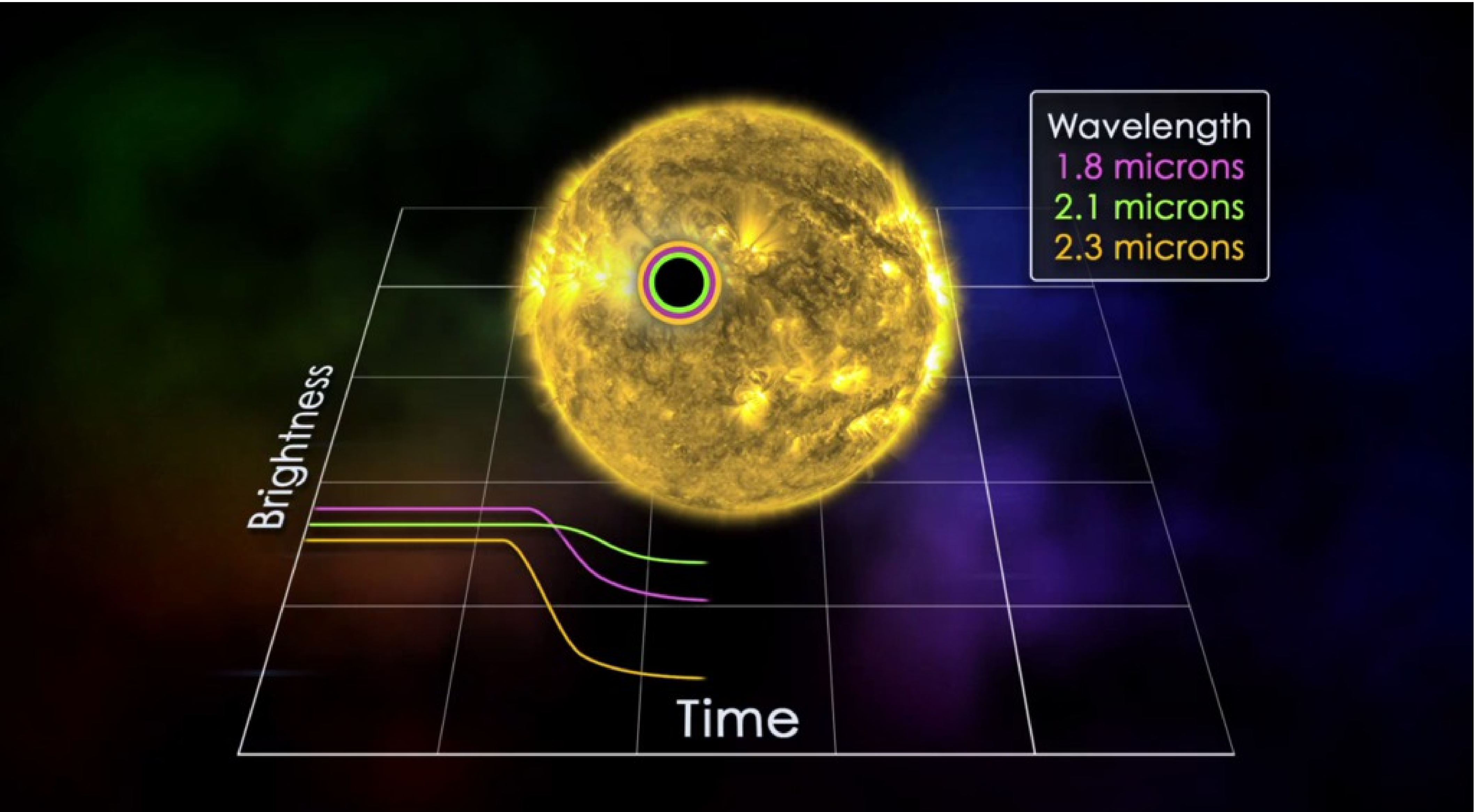
Transits



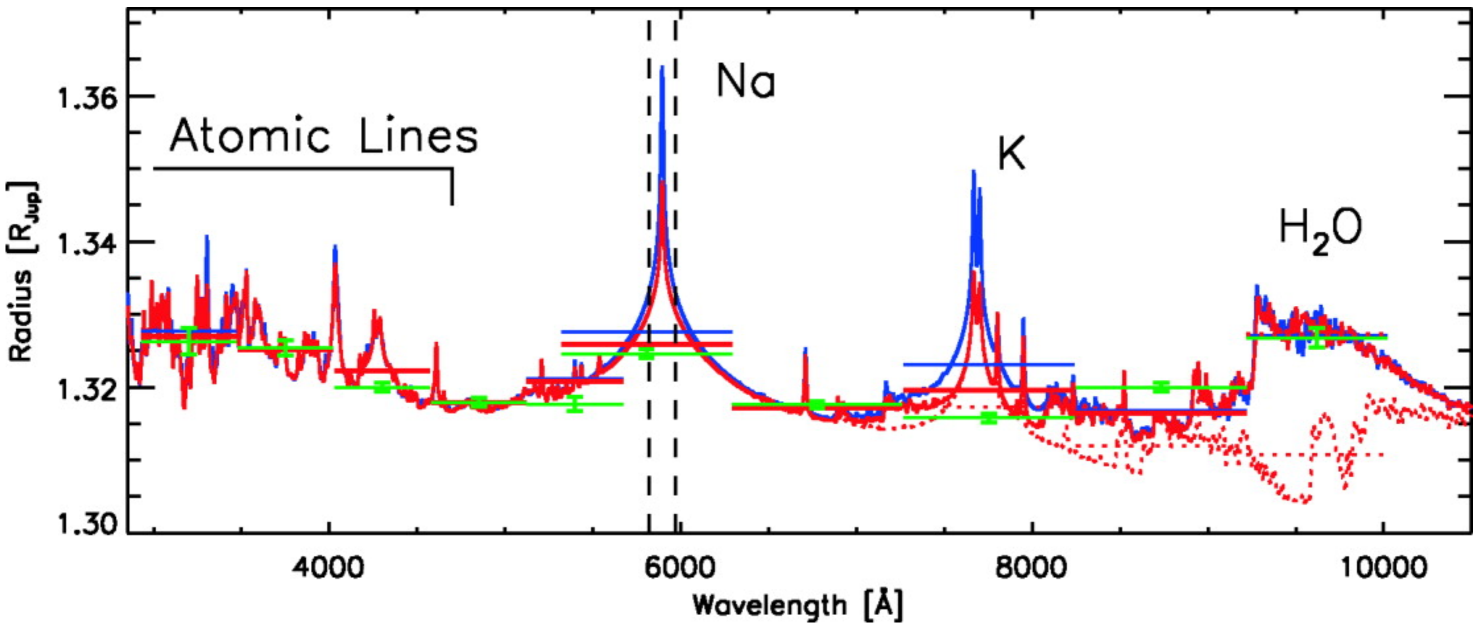
Effect of limb darkening (LD):
•LD of the star affects the shape of the transit.
•LD is larger at shorter wavelength.
•Transit is deeper and rounded at shorter lambda where LD is larger.

HST observations of HD209458b by Knutson et al. (2007).

Transit radius spectrum

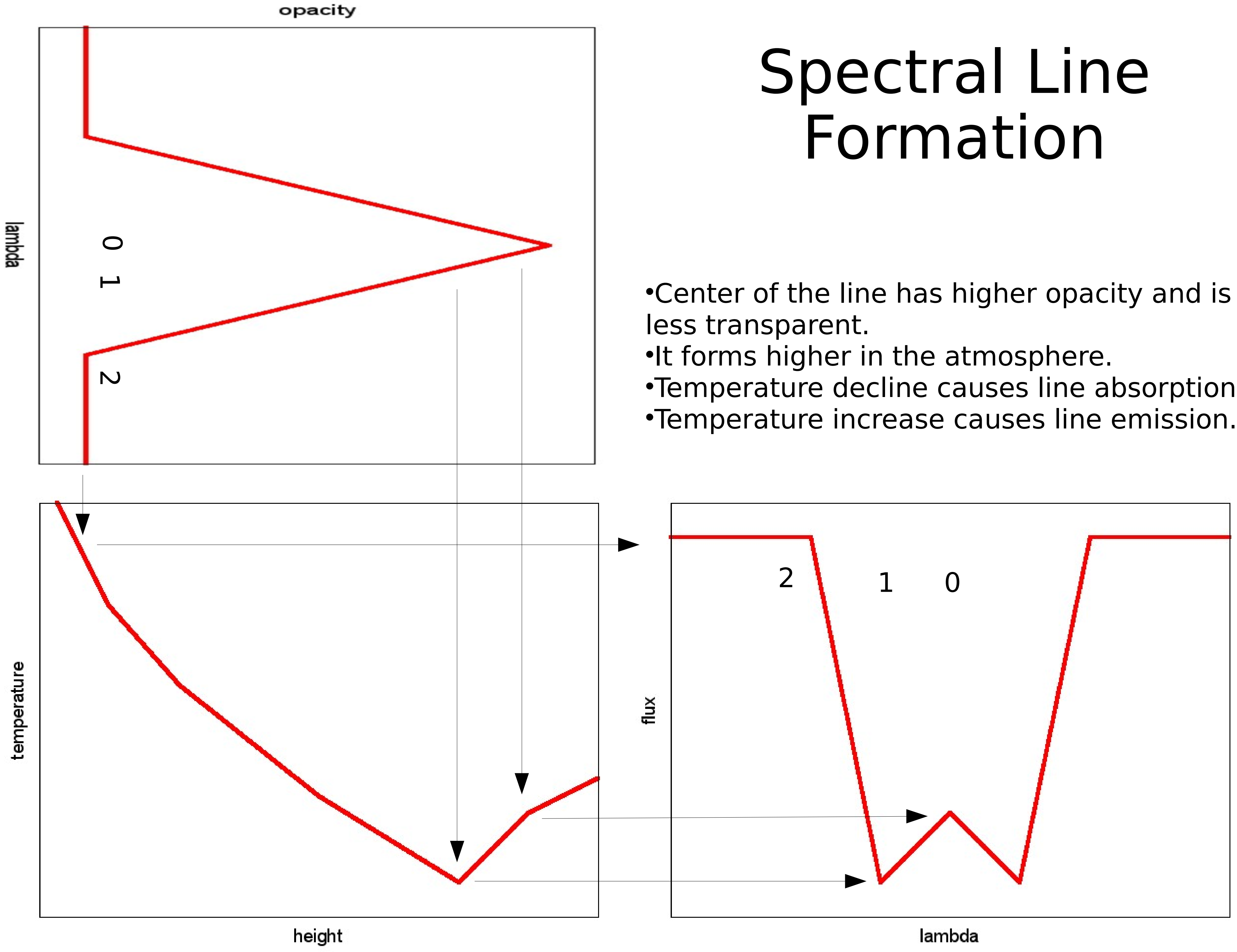


Transits radius spectrum



Effect of the planetary atmosphere:
Radius of the planet depends on the wavelength.
Theoretical calculations of Barman T., 2007, ApJ, 661, L191.
Baseline model with rainout. Red - with Na and K photoionization, blue- without, dotted – with H2O opacity excluded, red and blue horizontal bars – averaged over the interval, green horizontal bars measurements of Knutson et al. (2007).

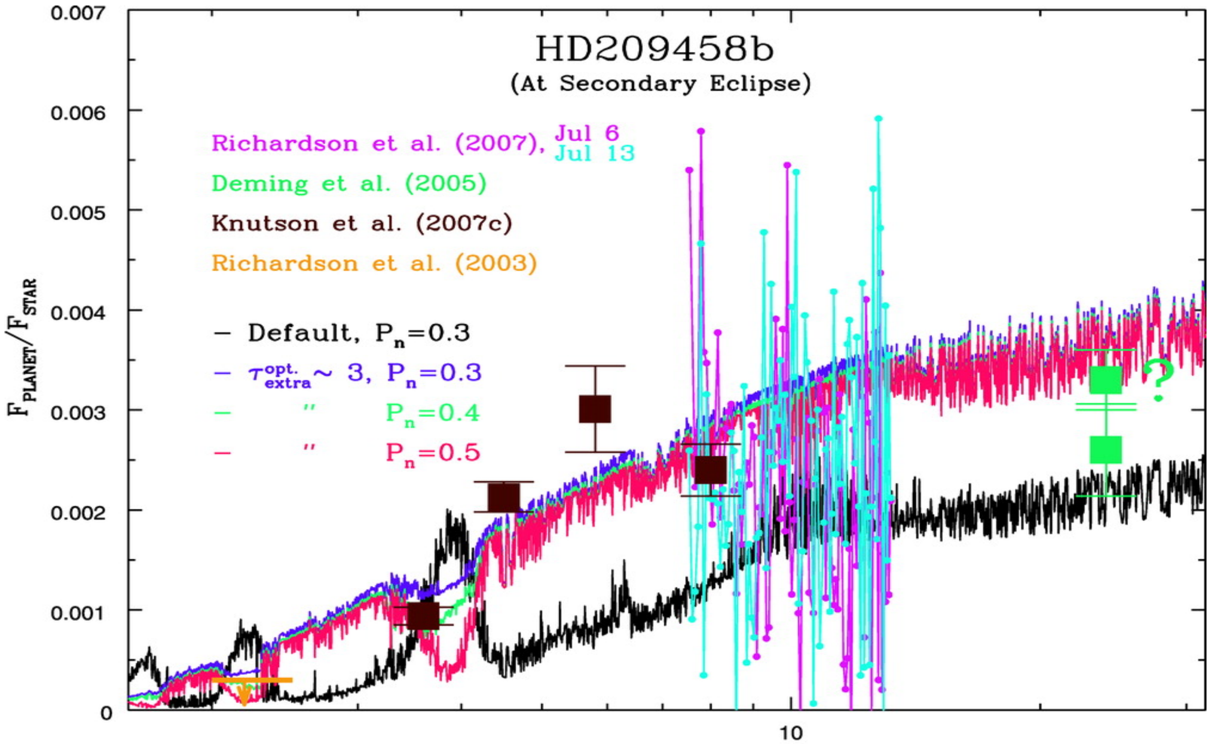
Spectral Line Formation



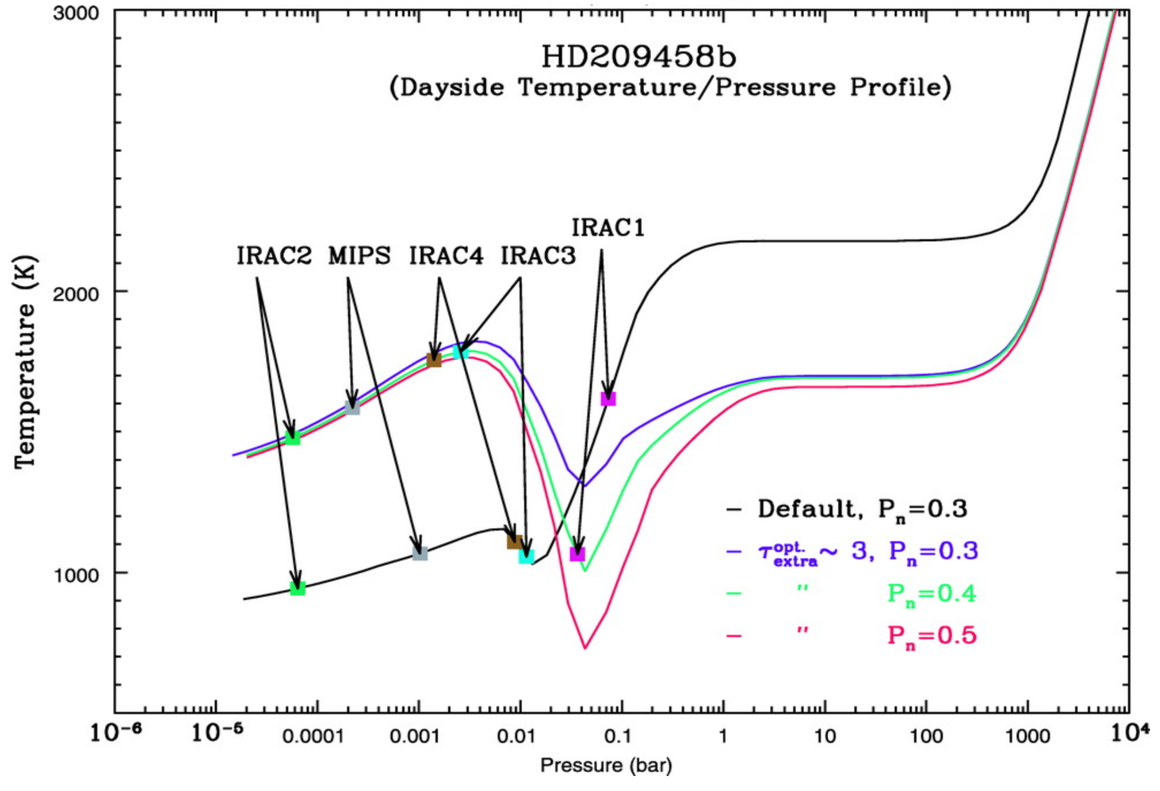
- Center of the line has higher opacity and is less transparent.
- It forms higher in the atmosphere.
- Temperature decline causes line absorption.
- Temperature increase causes line emission.

Occultations

Star+planet observed out of occultation. Only star observed during occultation. Difference is the spectrum of the planet at full phase.



K-band + Spitzer infrared observations and models of the planet/star flux ratio during the secondary eclipse

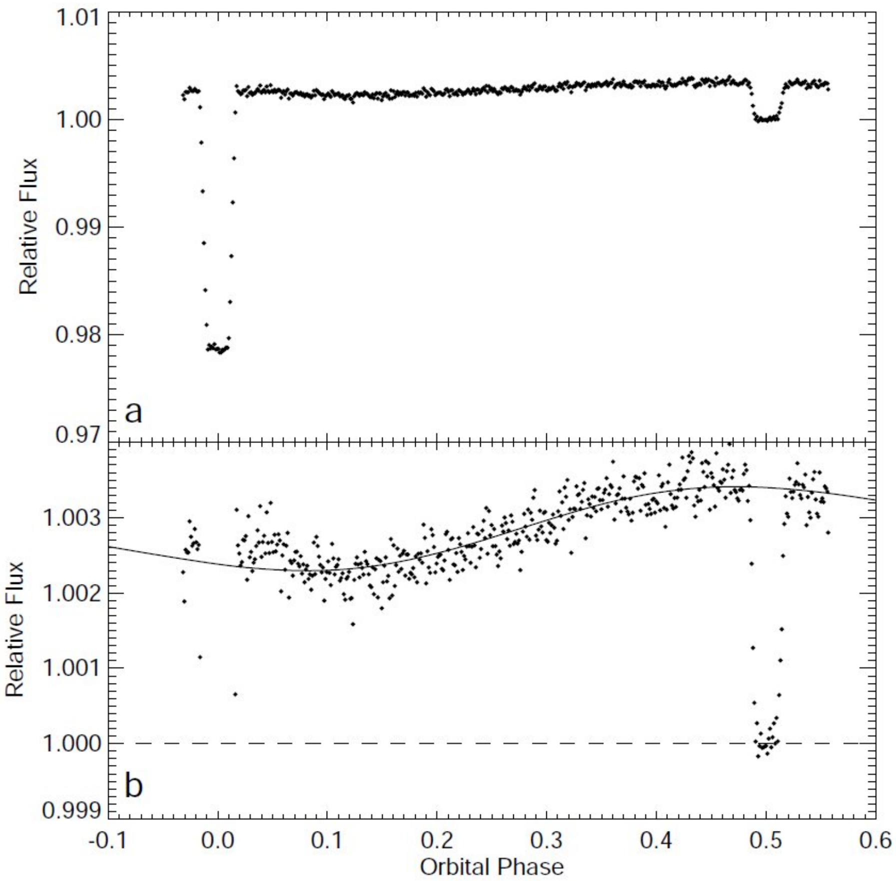


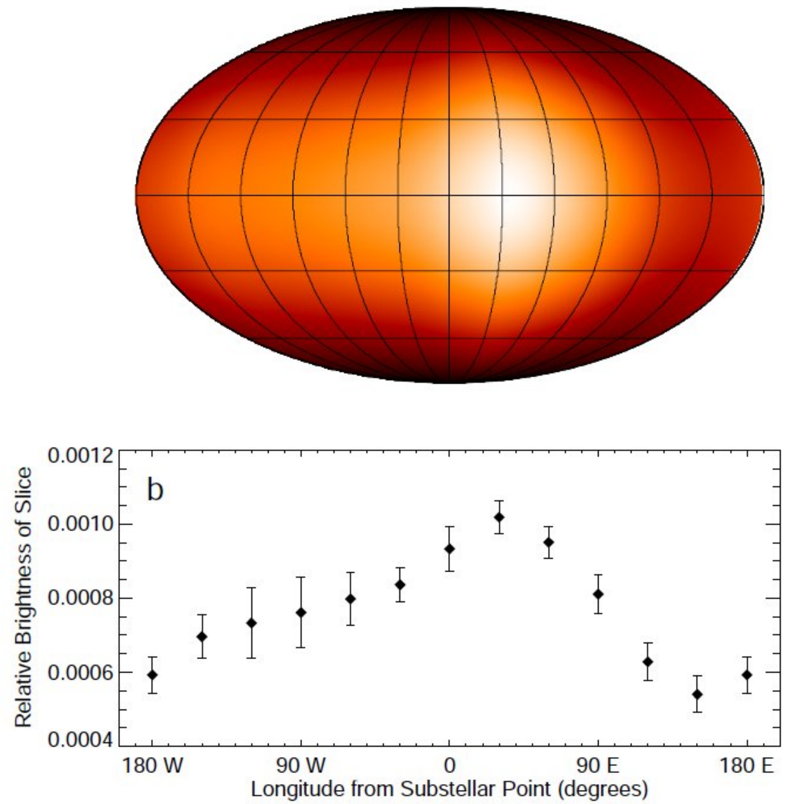
Theoretical T-P profile of the day side atmosphere of HD209458b calculated with Cool-Tlusty

Burrows, Hubeny, Budaj et al. 2007

Phase light curves

- Light-curve of the HD189733b on 8 micron. Amplitude of the LC depends on the day-night contrast and inclination. If we know the inclination as in this case one can construct a map. It reflects the efficiency and hydrodynamics of the heat transport. Knutson et al. 2007, Nature, 447, 183.

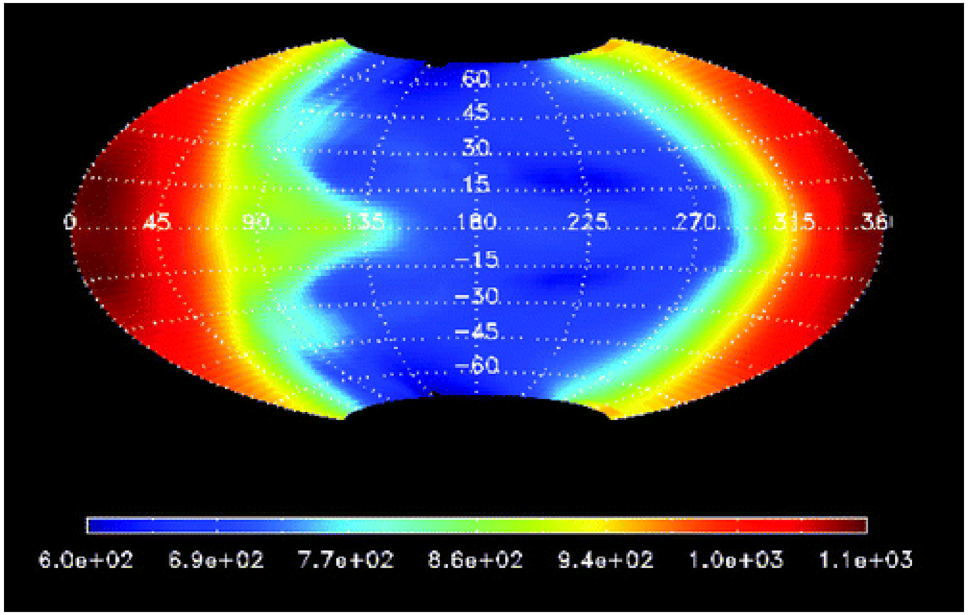


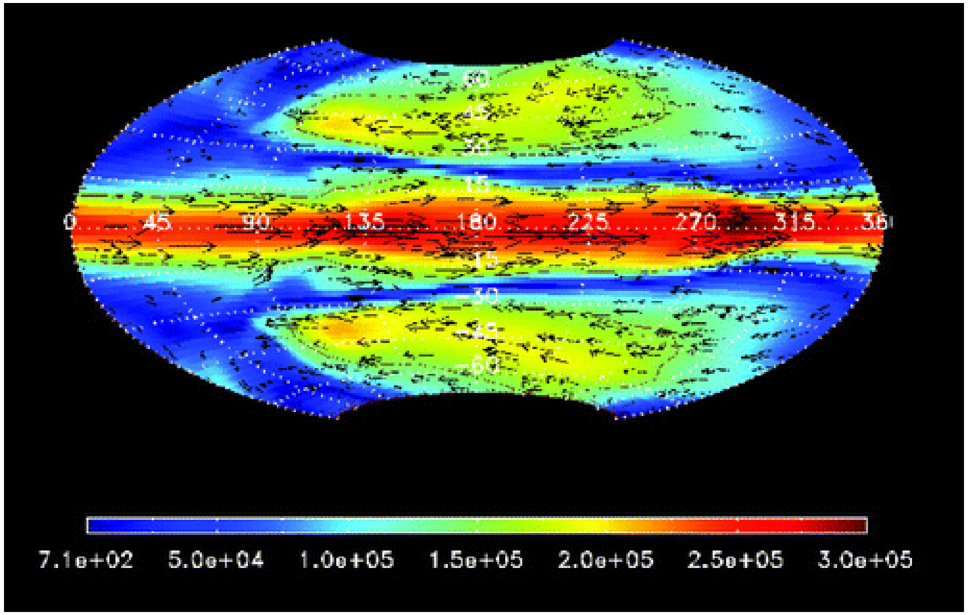


Day-night heat transport

• Generally, exo-planet atmospheres are not in hydrostatic equilibrium (HE) and may be quite dynamic. It is to be determined by the observations if the assumption of HE is satisfactory.

•3D hydrodynamical simulation of a rotating hot Jupiter from Dobbs-Dixon & Lin, 2008, ApJ 673, 513. Left panel shows the temperature distribution at the photosphere of the planet. Night side temperature is sensitive to the opacities and the depth where the day-night heat transport occurs. It increases for lower opacity models. Right panel – the velocity field, it decreases with decreasing opacity.



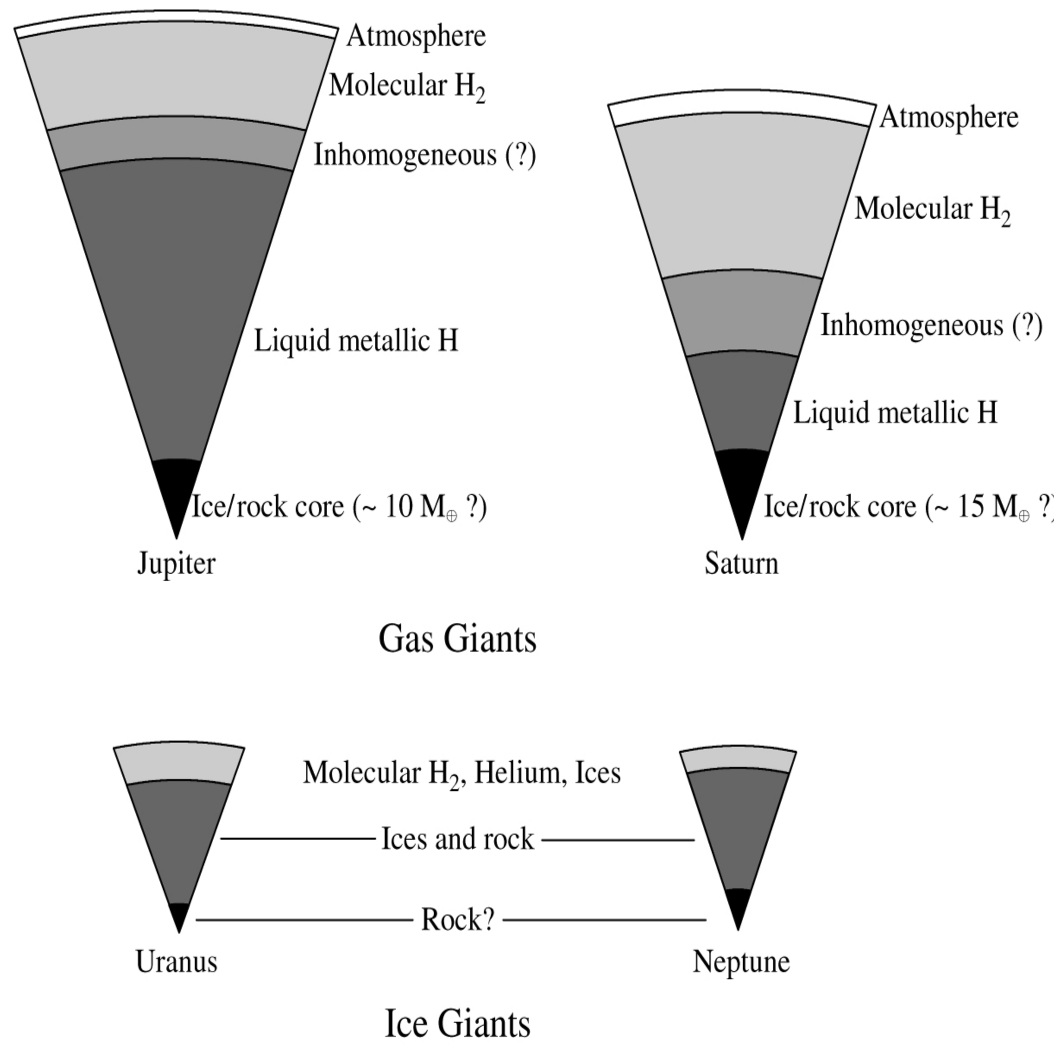


Ďakujem za pozornosť !

Na Mraky J.B.

Interior of giant planets

- Convective
- Partially degenerate
- Evolution affected by irradiation
- Cools and shrinks



Interior of the solar system giant planets

TESS

•TESS (transiting exoplanet survey satelite), NASA+MIT, search for nearest transiting rocky planets. Launched April 2018, 2yrs. First spaceborn all-sky survey (85%of sky), focus on bright stars V<10mag, 200 thousand MS dwarf stars (cooler than Kepler).

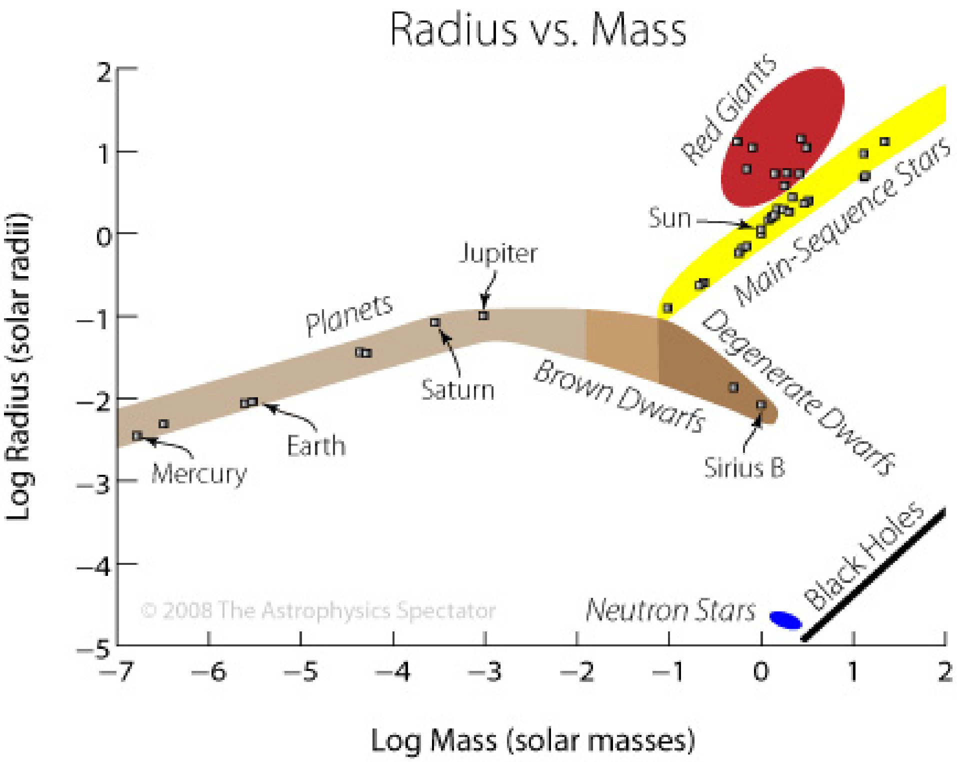
• 4 cameras, each 10cm lens in diameter, with 24x24 deg^2 field and 4 CCDs, 1pixel=21arcsec, 600-1000nm passband. FoW 24x96deg^2.

•Will tile the sky with 26 sectors (24x96 deg^2), 27 days at each sector, 2min cadence, full frame images 30min cadence

•high Earth elliptical orbit, orbital period=13.7d in 2:1 resonance with the Moon

Mass-radius relation

Notice that planets and brown dwarfs are not completely degenerate but are somewhere between the white dwarfs and the Sun. Also only electrons are degenerate not ions.



Degeneracy tends to conserve the product of the mass and volume

$$M\,V = constant$$

Coulomb forces tend to keep the distance between the charges (constant density) and conserve the mass to volume ratio.

$$\frac{M}{V} = constant$$

The competition of the degeneracy and Coulomb effects are responsible for approximately constant radii of brown dwarfs and extrasolar planets, of the order of Jupiter radius, over 2 orders of masses from 0.1 Msun up to 1Mj. Degeneracy prevails in brown dwarfs and Coulomb effects in planets.

Extrasolar Enigmas: from disintegrating exoplanets to exoasteroids, and exocomets

Ján Budaj

Astronomical Institute, Slovak Academy of Sciences

Tatranská Lomnica, Slovak Republic

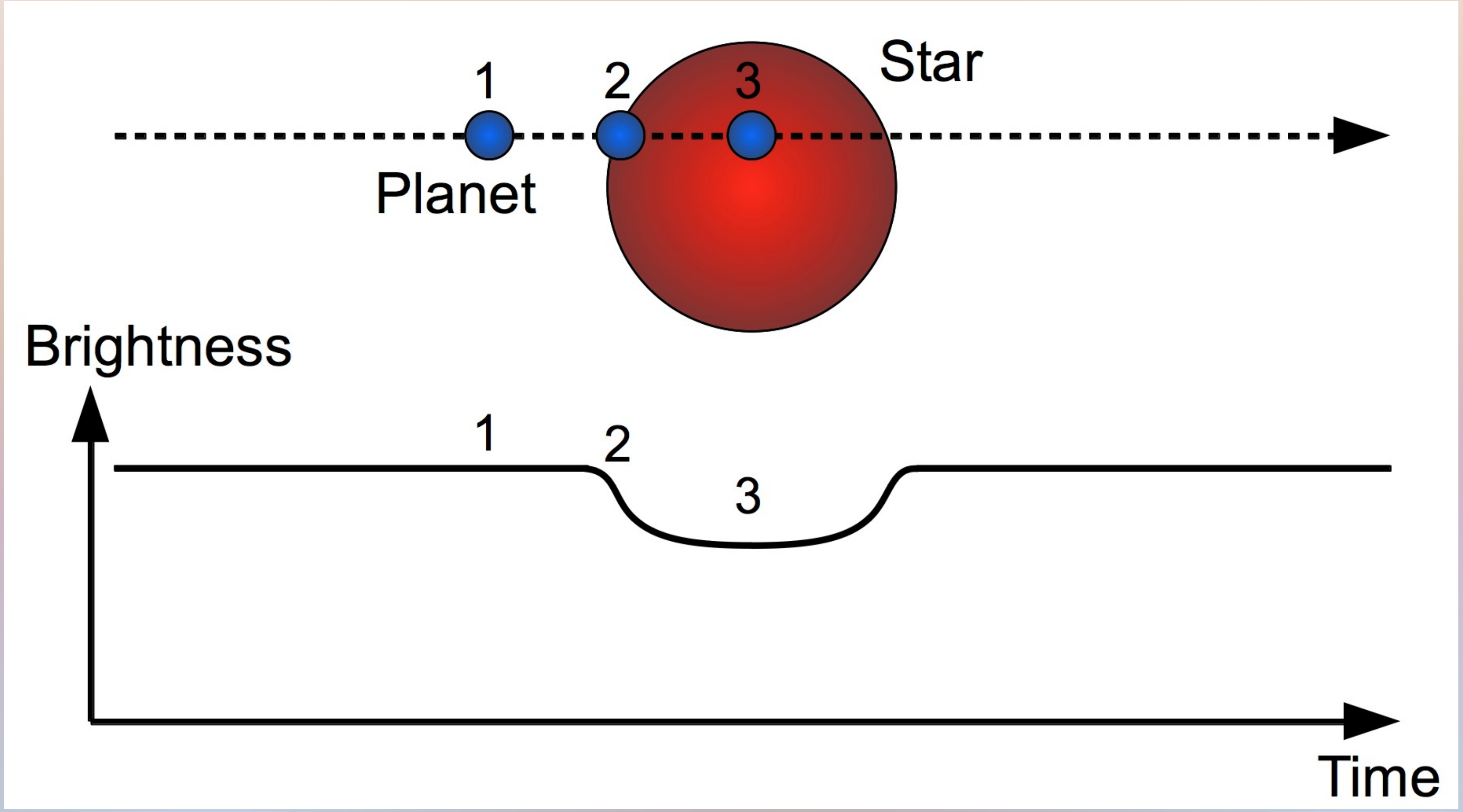
SPACE::TALK, Kosice, Dec. 5, 2019

Content

- Disintegrating exoplanets
  - KIC 1255b, K2-22b, KOI 2700b
- Exoasteroids
  - WD 1145, ZTF J0139
- Exocomets
- EPIC 204376071 (a single 80% dip, young M5 star), HD 139139 (28 random dips)
- Boyajian’s star

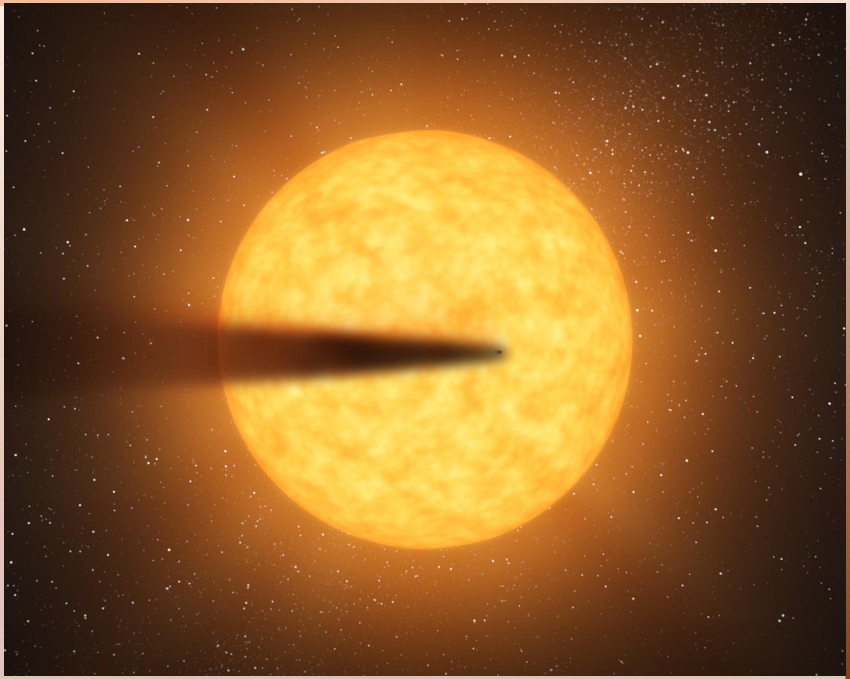
Transit of the planet

Thousands of ‘normal’ exoplanets were discovered using the transit method, but there are a few black sheep...

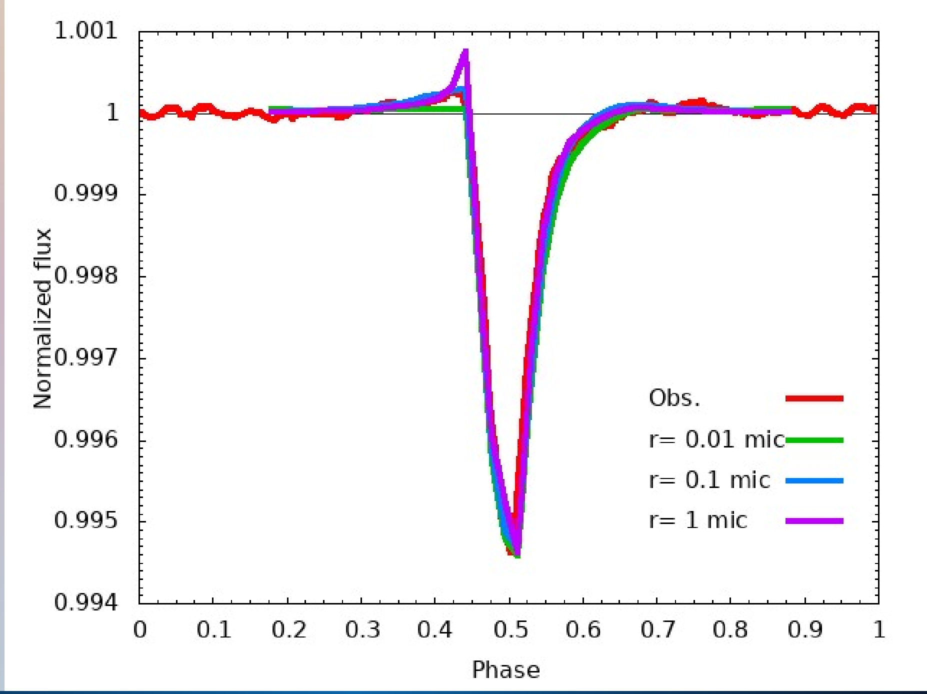


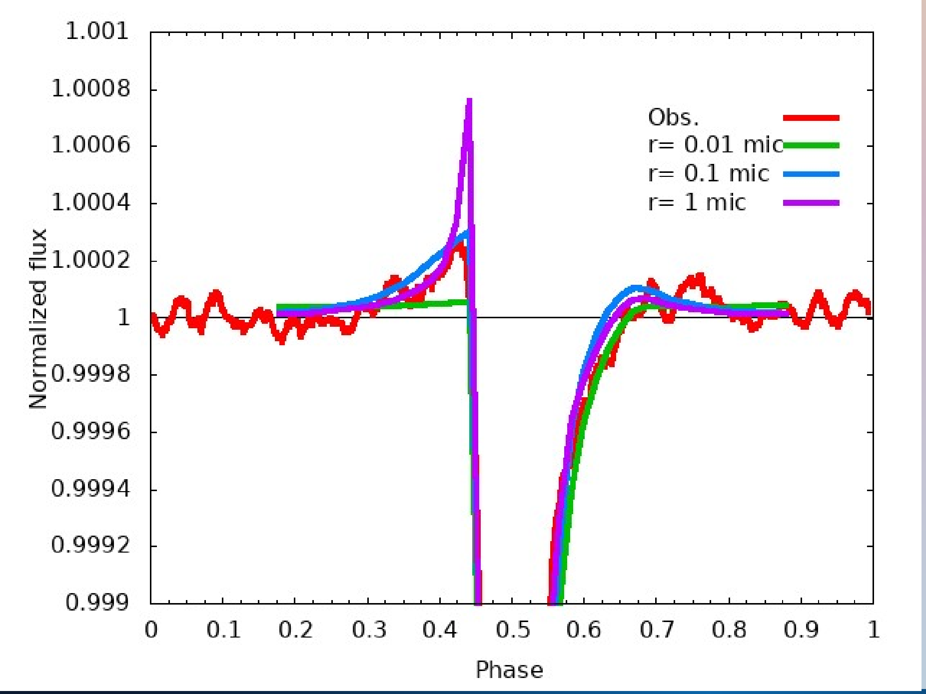
Exo-planet or exo-comet?

- KIC12557548 (Kepler 1520b)
- Discovered with Kepler by Rappaport et al. (2012)
- K4-7V star, V=16mag
- Variable transit depth, 0-1.2%, sometimes missing
- Strictly periodic, P=16h
- Asymmetric transit



Budaj (2013)

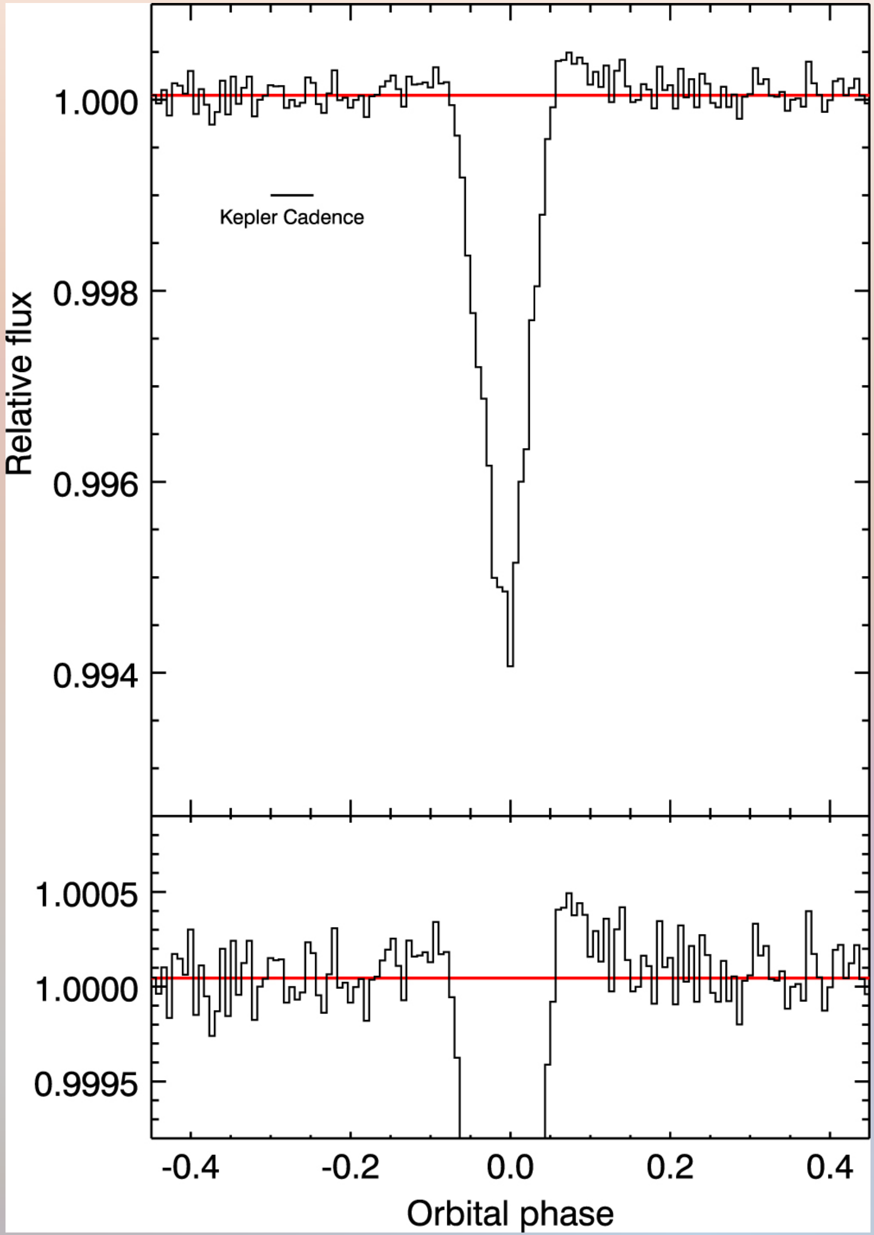




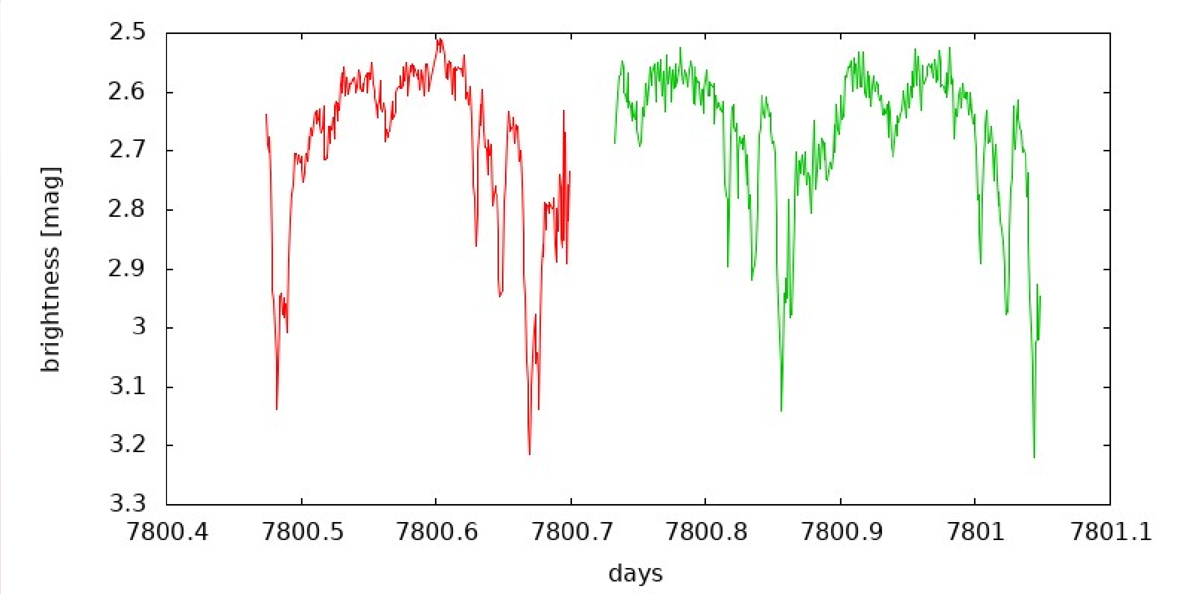
Exo-planet: K2-22b

Sanchis-Ojeda et al. 2015
K2 Kepler mission
M0V red dwarf
variable transits 0-1.3%
P=9.1 h
asymmetric transits
post-transit brightening

Star fainter => planet irradiation smaller
=> radiation pressure not strong enough
to blow the dust away from star.

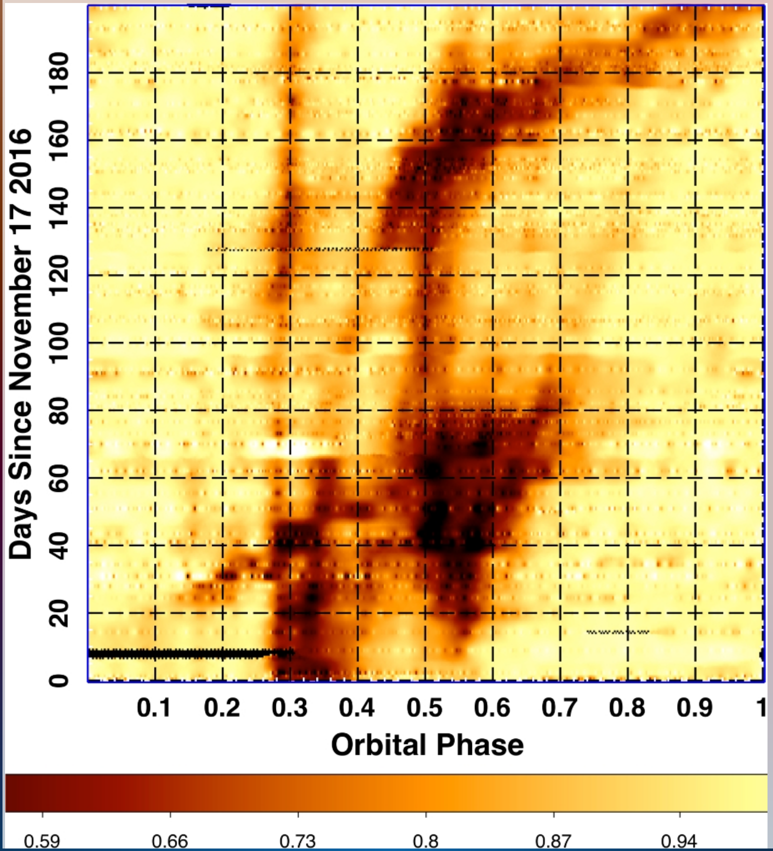


Exo-asteroids: WD 1145+017



Budaj et al. in prep.

Rappaport et al. 2018



Vanderburg et al. 2015
K2 Kepler mission
white dwarf=>small object=>deep eclipses
a set of deep eclipses up to 55%
variable (different periods), P=4.5h
more than 6 bodies -asteroids
circumstellar dust+gas

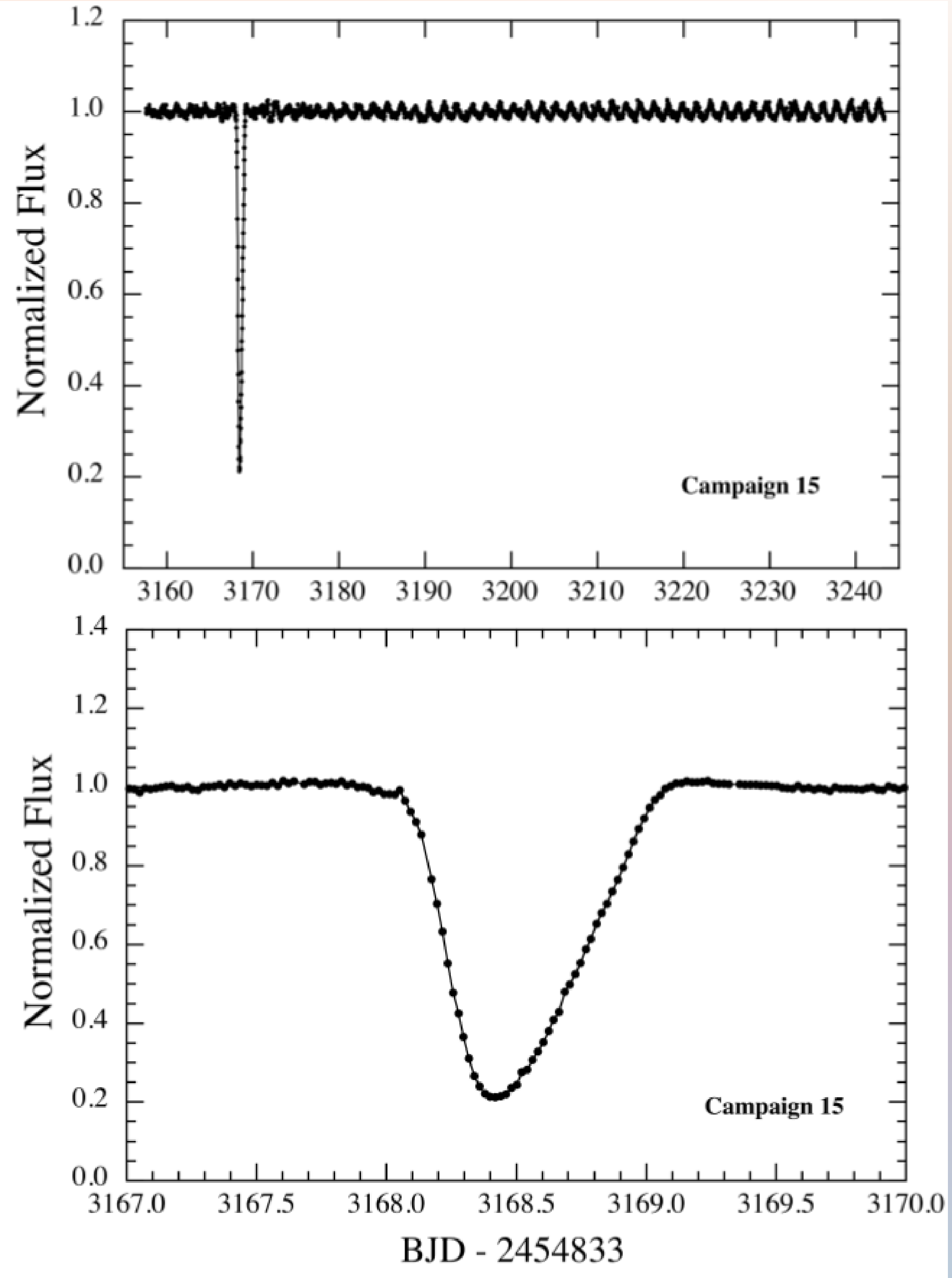
solves a problem of metals in WD atmospheres

06:28:23 PM

EPIC 204376071

Rappaport et al. 2019
K2 mission, two campaigns
M5 dwarf
Upper Sco associaton, 10 Myr
A single asymmetric dip, 80% deep
no other activity apart from spots
and flares over 160 days

An occultation by an inclined disk?



06:28:23 PM

Exo-comets

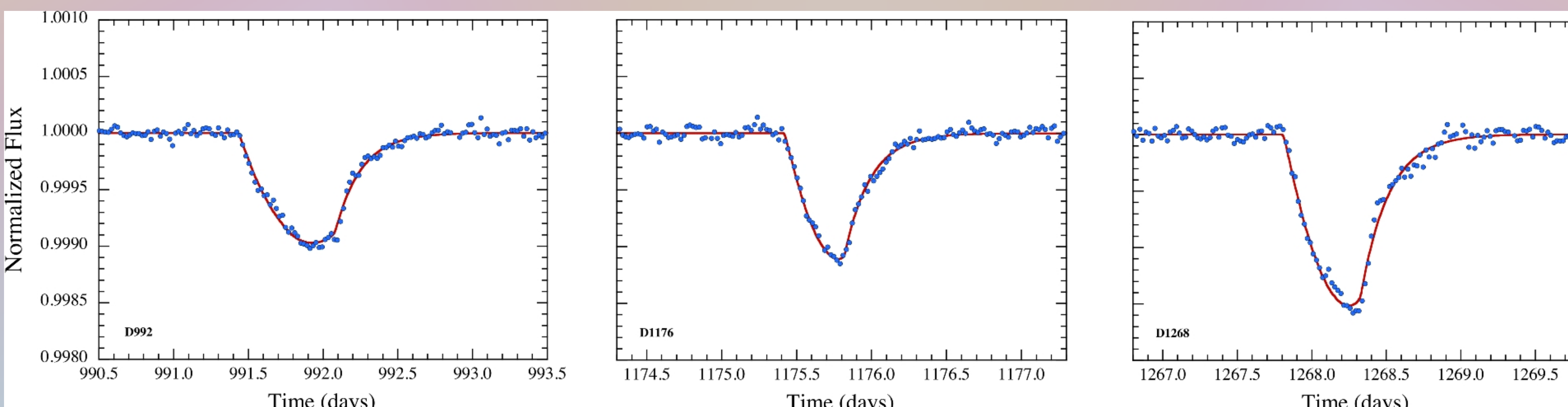
Rappaport et al. 2018
Kepler
KIC 3542116, F2V
-three deeper transits 0.1%, last 1 day
-three shorter and shallower transits
KIC 11084727, similar to KIC3542
one event
No periodicity in either case

Kennedy et al. 2019
Kepler
KIC 8027456
one asymmetric transit

Zieba et al. 2019
TESS
Beta Pic
Three dips

Ansdell et al. 2019
K2 mission
EPIC 205718330, EPIC 235240266
episodic dips with complicated shapes
depth 0.1-1%
duration 0.5-1 day

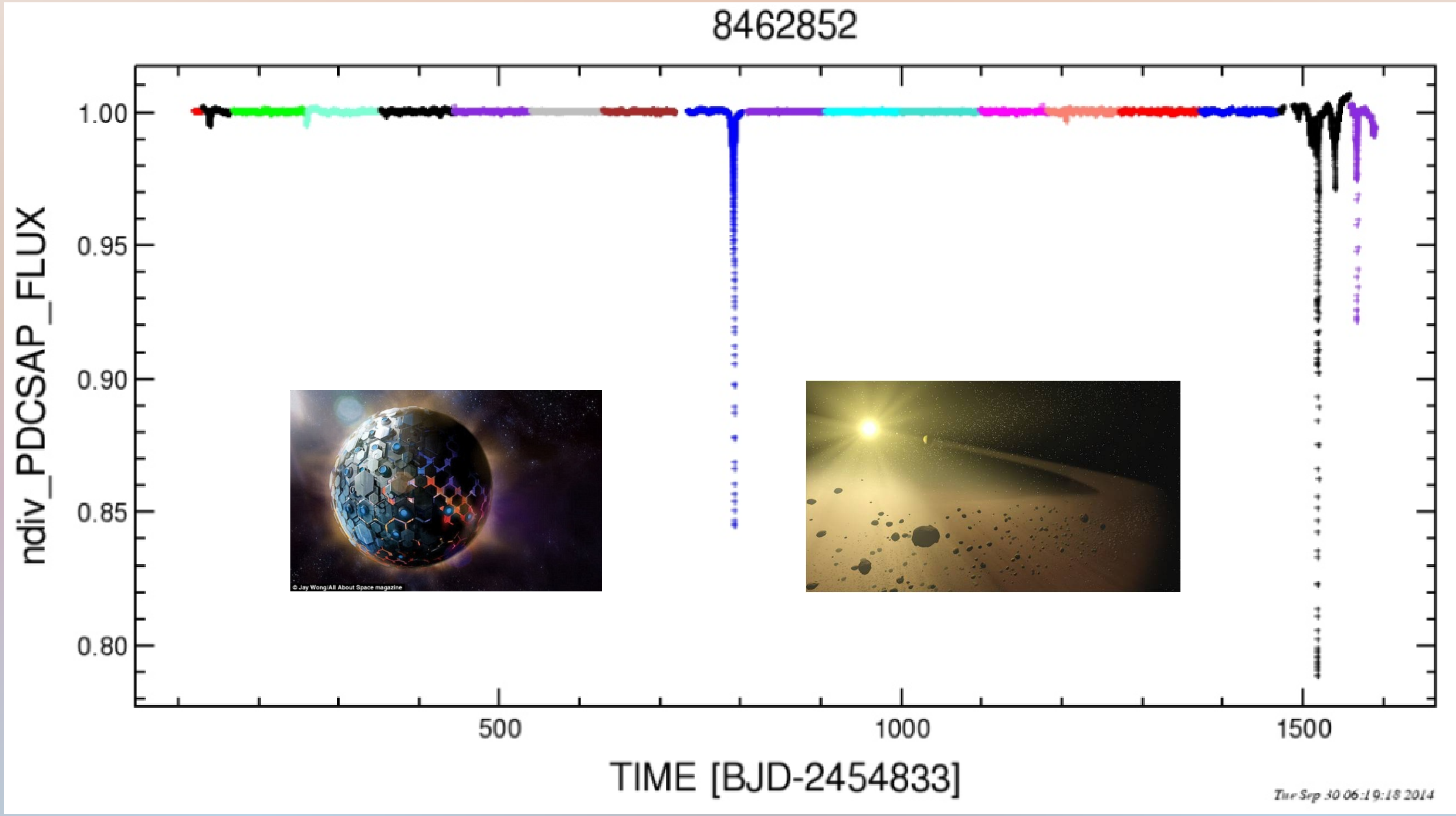
Rappaport el al. 2018



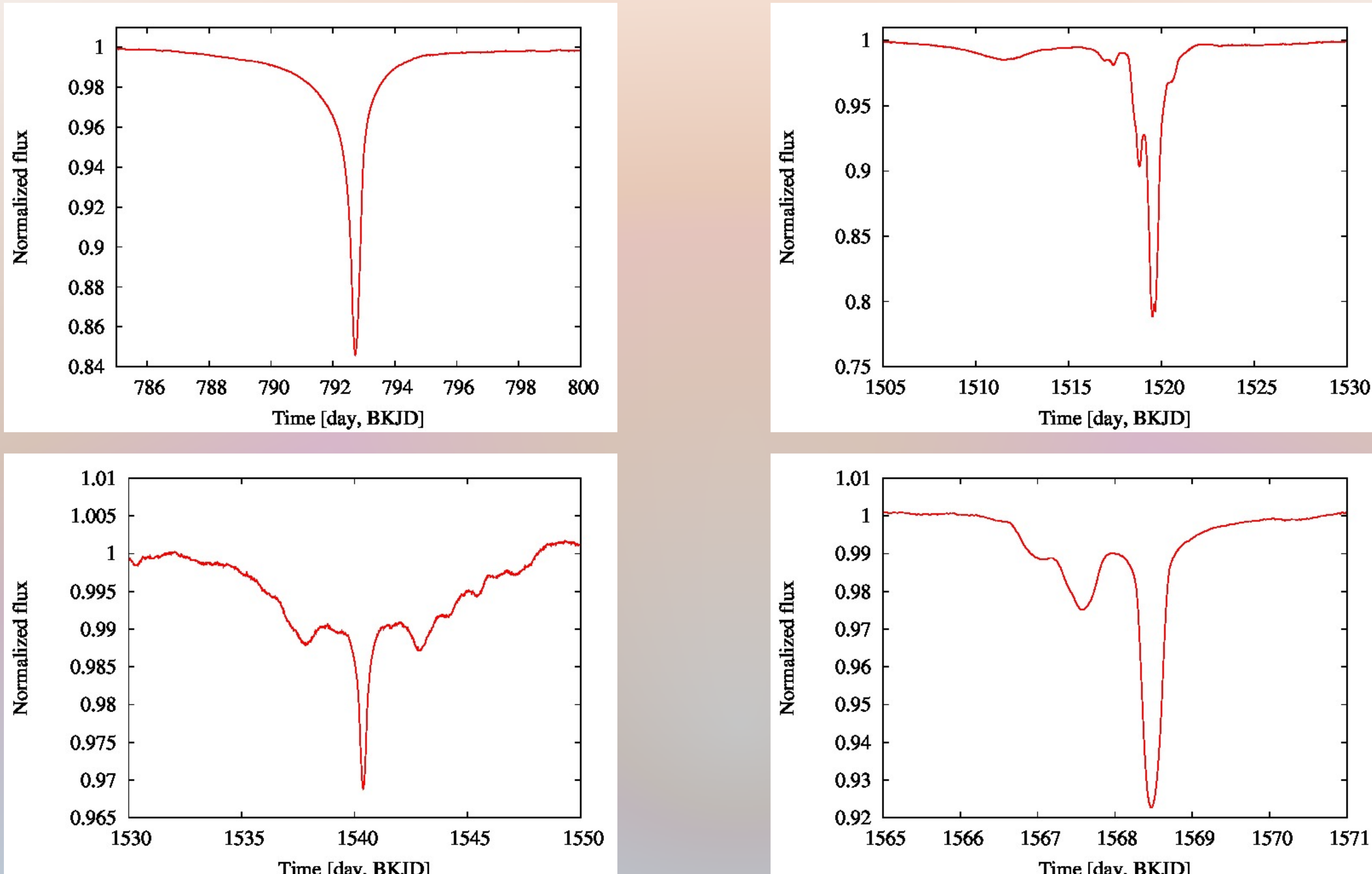
06:28:23 PM

Boyajian‘s star (KIC 8462852)

- Boyajian et al. (2016), Kepler data, normal 12 mag F3V(IV) star
- M=1.43Msol, R=1.58Rsol, Teff=6750K
- Irregular dips with peculiar shapes, up to 20% deep

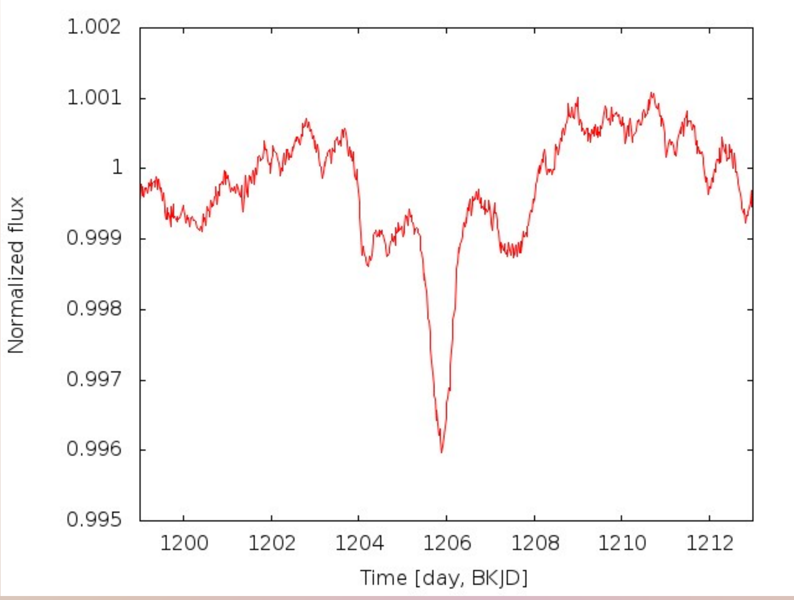


Shapes of four main events



06:28:23 PM

Another Kepler event



Follow up

IR,sub-mm,mm,GAIA

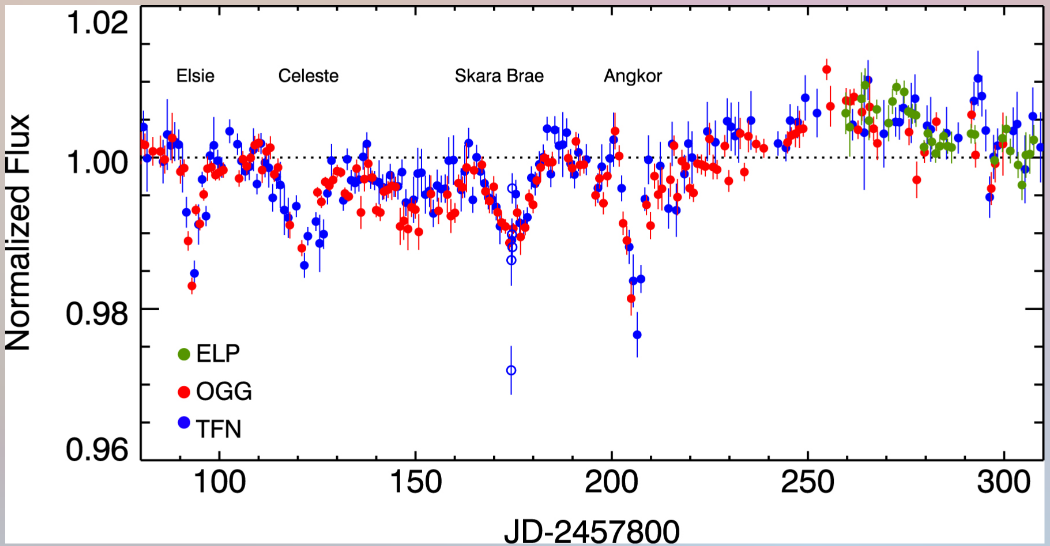
- Boyajian et al.2016, Marengo et al. 2016
- Lisse et al. 2015, Thompson et al. 2016
- Hippke & Angerhausen 2017 (GAIA, 390pc)
- Nondetection, not young object
- Dust <7.7 M_Earth within 200au
- Dust in occultation < 10^-3 M_Earth

Star was quiet 2013 May – 2017 May

Star wakes up 2017

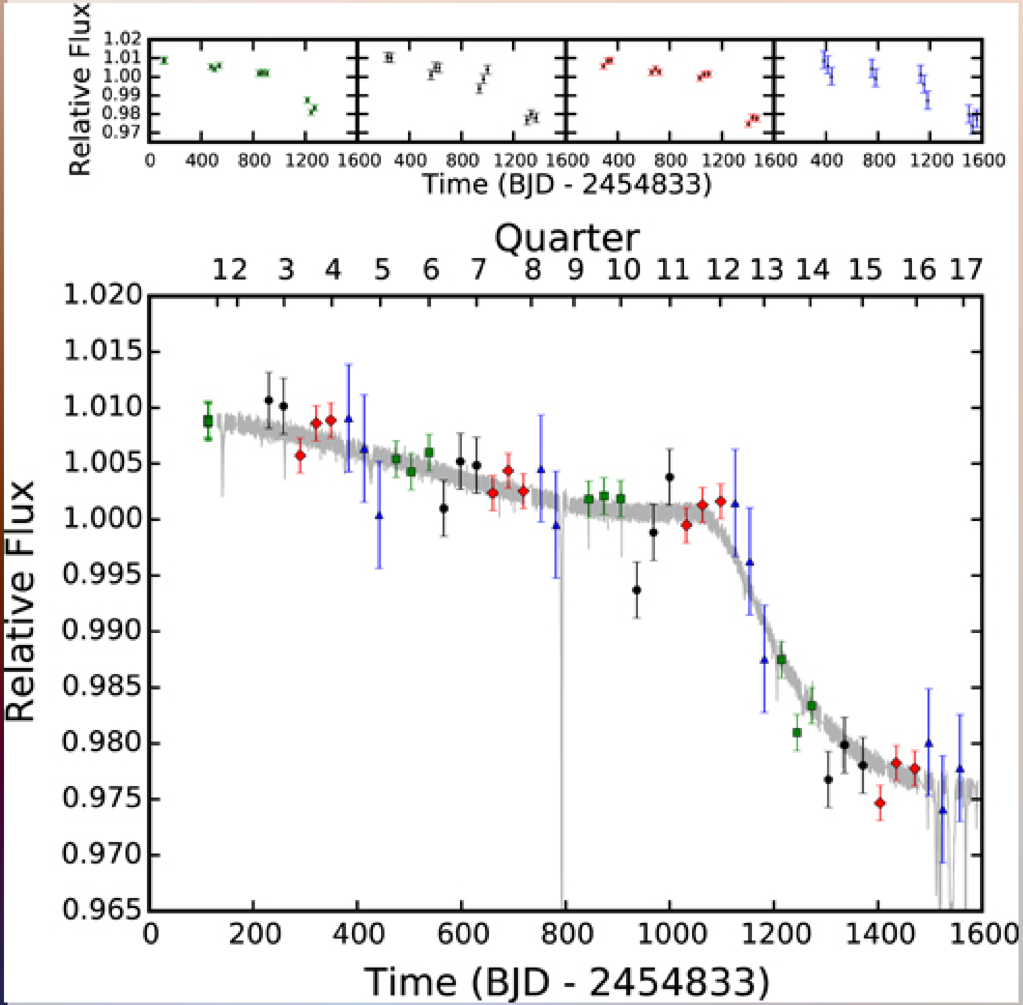
Ground based obs and chromatic variability

Compatible with dust and particle size 0.1 mic (Boyajian et al. 2018)



06:28:23 PM

Long term variability



Fading during the Kepler mission (Montet & Simon 2016)

From 1890 to 1989 the star faded by 0.16 mag/cen
Schaefer (2016), Castelaz & Barker (2018)

Dimming & brightening spells (Meng et al. 2017, Gary & Bourne 2017, Simon et al. 2018, Hippke & Angerhausen 2018)

Model : Dust distributed along a single elliptical orbit (Wyatt et al. 2018)

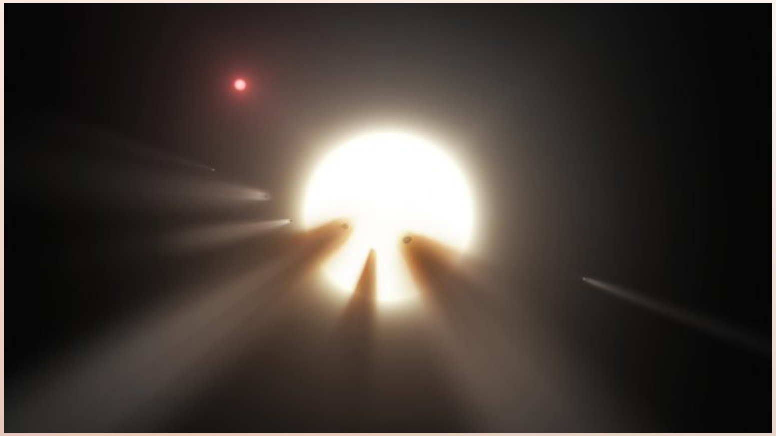
Currently 12% dimming => 10^-3M_Earth of dust that must be continuously replenished (Schaefer et al. 2018)

06:28:24 PM

Plenty of ideas:

-objects within our own solar system
-an interstellar material or objects
-circumstellar material (evidence mounting)
-**comets** (favoured by the discoverers)
-**dust-enshrouded planetesimals**
-**brown dwarf with rings**
-late heavy bombardment
-intrinsic stellar variability
-star swallowing planets/asteroids
…
-alien megastructures (most citations)
...

Swarm of Comets



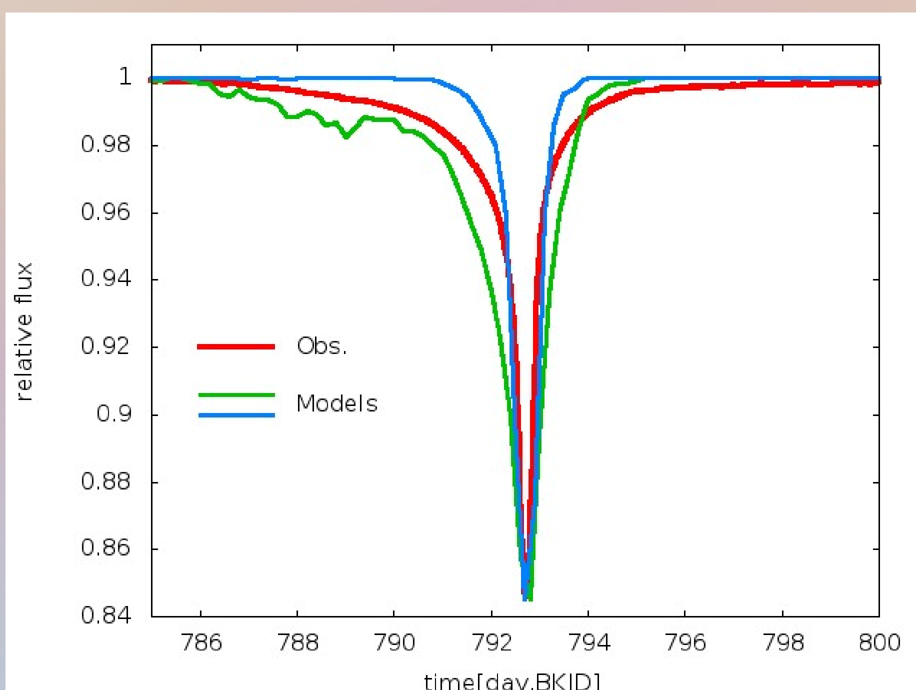
- Bodman & Quillen (2016)
  - a swarm of 70-700 comets
  - highly eccentric orbits
- Pros:
  - Fits most of the features very well
  - Satisfies the IR limits
  - Such comets are known to exist and have high probability of transit
- Cons:
  - cannot reproduce smooth 800d feature
  - produce shallower egress with tails (obs. have the opposite trend)
  - many free parameters can fit anything, hence the model may not necessarily be correct even if the fit is perfect
  - Symmetric 'ring like' feature at BKJD 1540 would be an accidental constellation of comets
  - Another symmetric feature at BKJD 1210 would be another accidental constellation of comets
  - Comets can barely produce and replenish 10^-3 M_Earth of dust causing long term variability

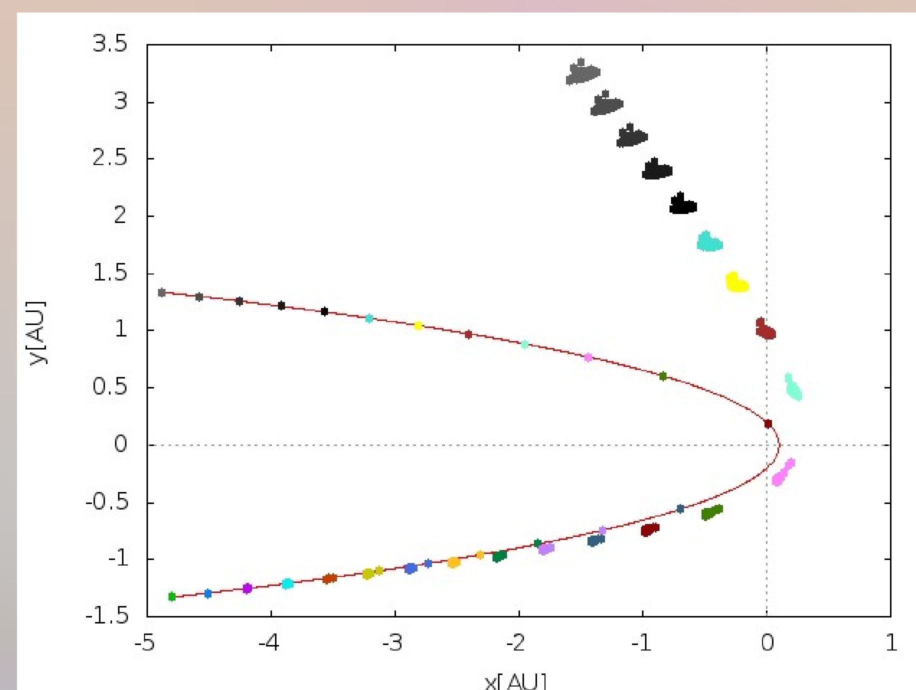
Asteroids wrapped in the dust

- Recipe in Neslusan & Budaj (2017). You will need:
- 1 star, 4+ massive bodies, dust to wrap, gravity (star+body), P-R drag
- Let it bake for a few months (MERCURY, Chambers 1999)
- Example solution found: 4 objects on almost identical orbits:

  i=90 deg, p=0.1 AU, a=50 AU and identical particles with beta=0.63

Spherical cloud (blue: M=10^-10 Mstar, green: 10^-8 Mstar

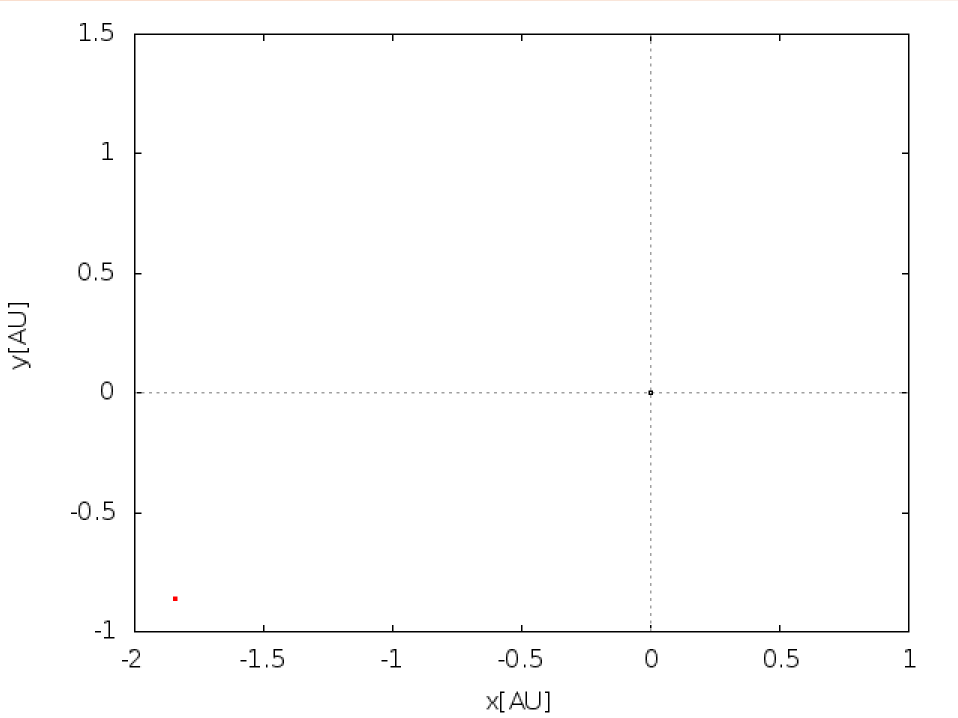


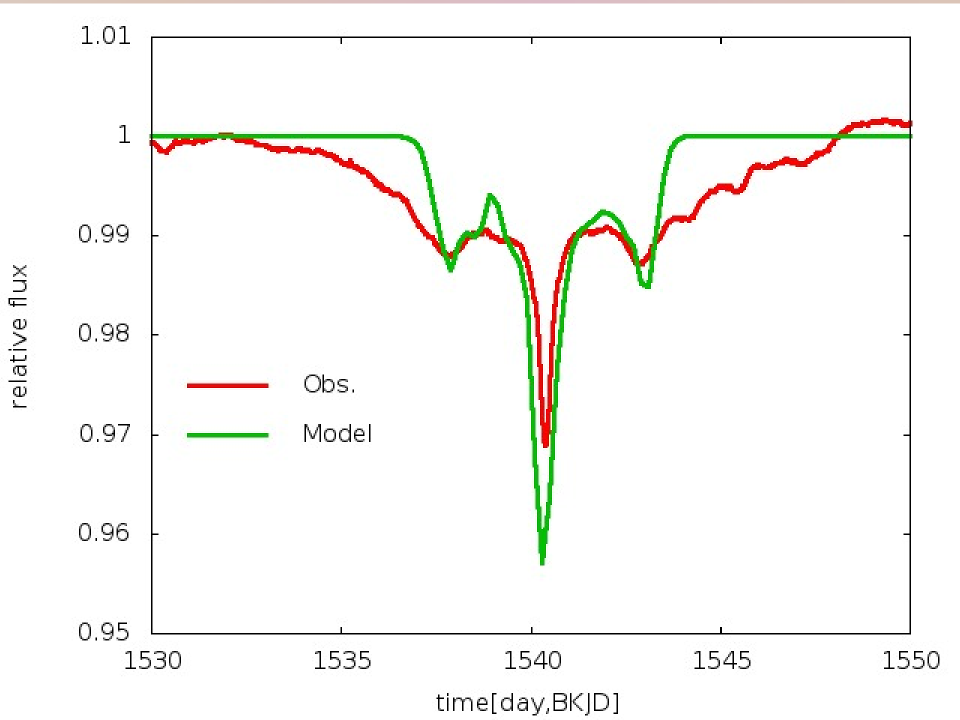


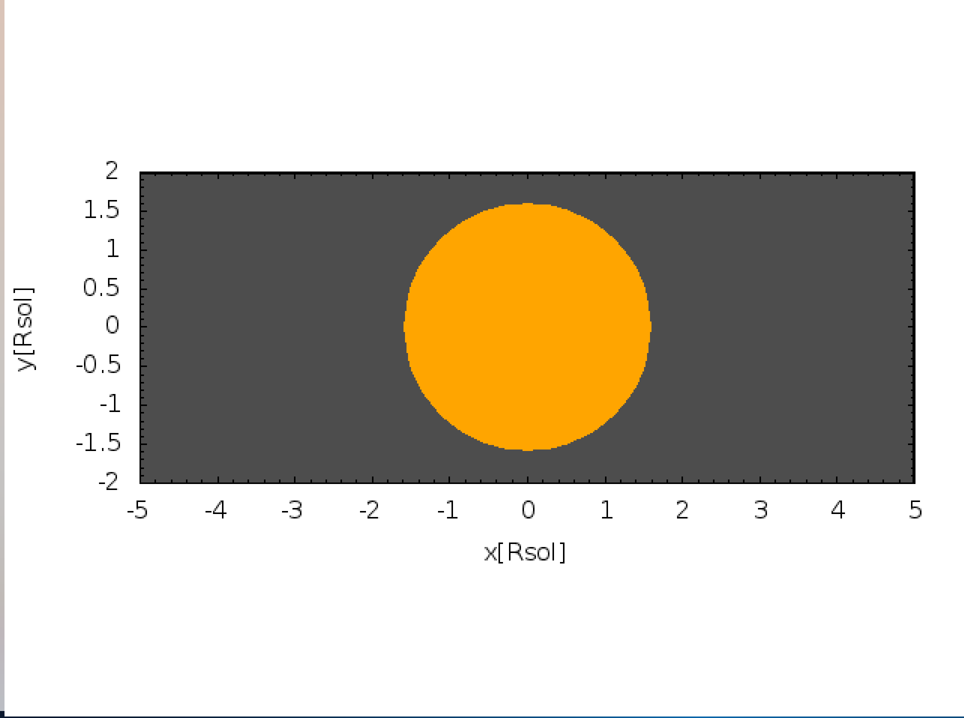
06:28:24 PM

Massive bodies wrapped in the dust

An initial ring-like cloud,
Inclination=45deg, R=5000-10000km,
M=10^-8 Mstar







06:28:24 PM

Massive bodies wrapped in the dust

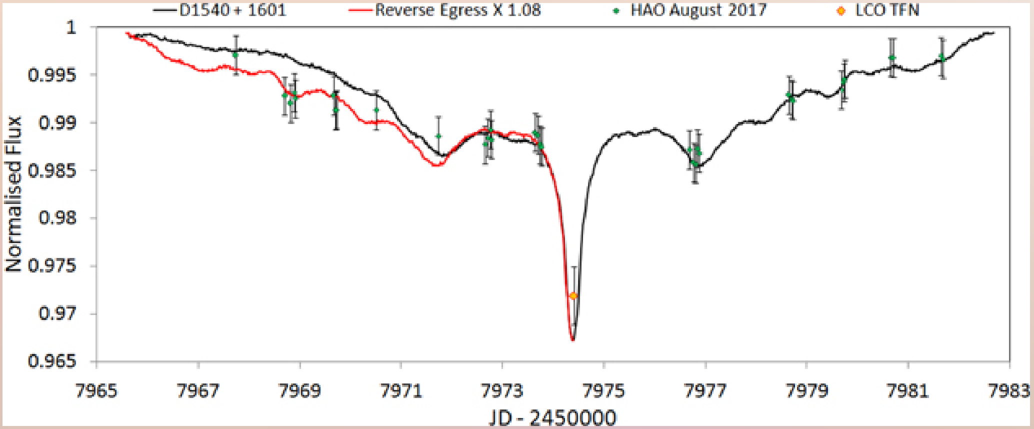
Pros:
-problems of the comet scenario are gone
-low number of free parameters
-can produce small or comet-like debris

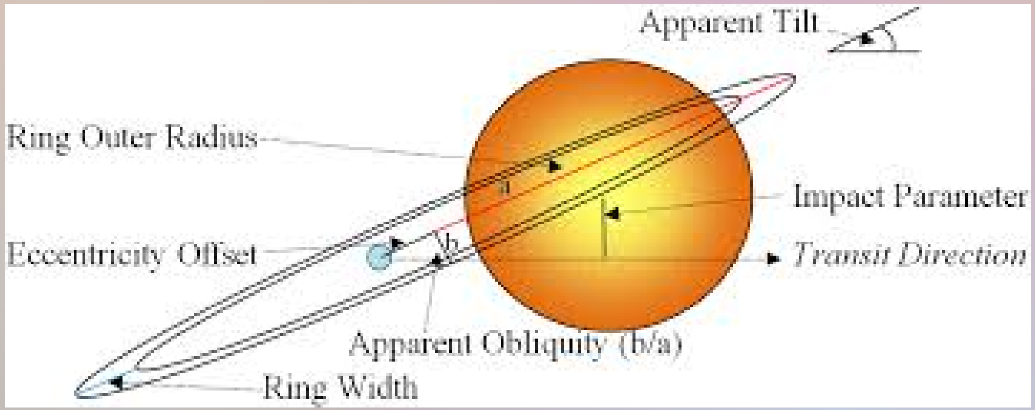
Cons and further questions:
-fits are not perfect (but surprisingly good given only a few free param)
-how to get a massive body on such eccentric orbit
-how to get 4 or more massive bodies on identical orbit
-how to form a dust cloud around it
-dust material is lost and not available for the next return

Granvik et al. 2016:
Super-catastrophic disruption of asteroids at small perihelion distances.

The Lord of the Rings

- Bourne, Gary & Plakhov (2018)
  - Skara Brae is similar to BKJD 1540
  - The Lord = a brown dwarf (4.4 yr, 3 au, mild eccentric orbit
  - + fellowship of 9 rings
- Pros:
  - Explains BKJD 1540 and Skara Brae
  - some repeating long term variability
  - Prediction for "return of the king" or new eclipse on 27.12.2021
- Cons:
  - Does not explain other features
  - Mass, period & ring sizes are close to observational and theoretical limits





06:28:24 PM

Boyajian's star is still active ...

TESS detected a 1.5% deep, 1 day long dimming event on Sep.4, 2019

to be continued ...

Thank you!

Supported by the grants: VEGA 2/0031/18, APVV 15-0458, and ERASMUS+(Per Aspera ad Astra Simul).