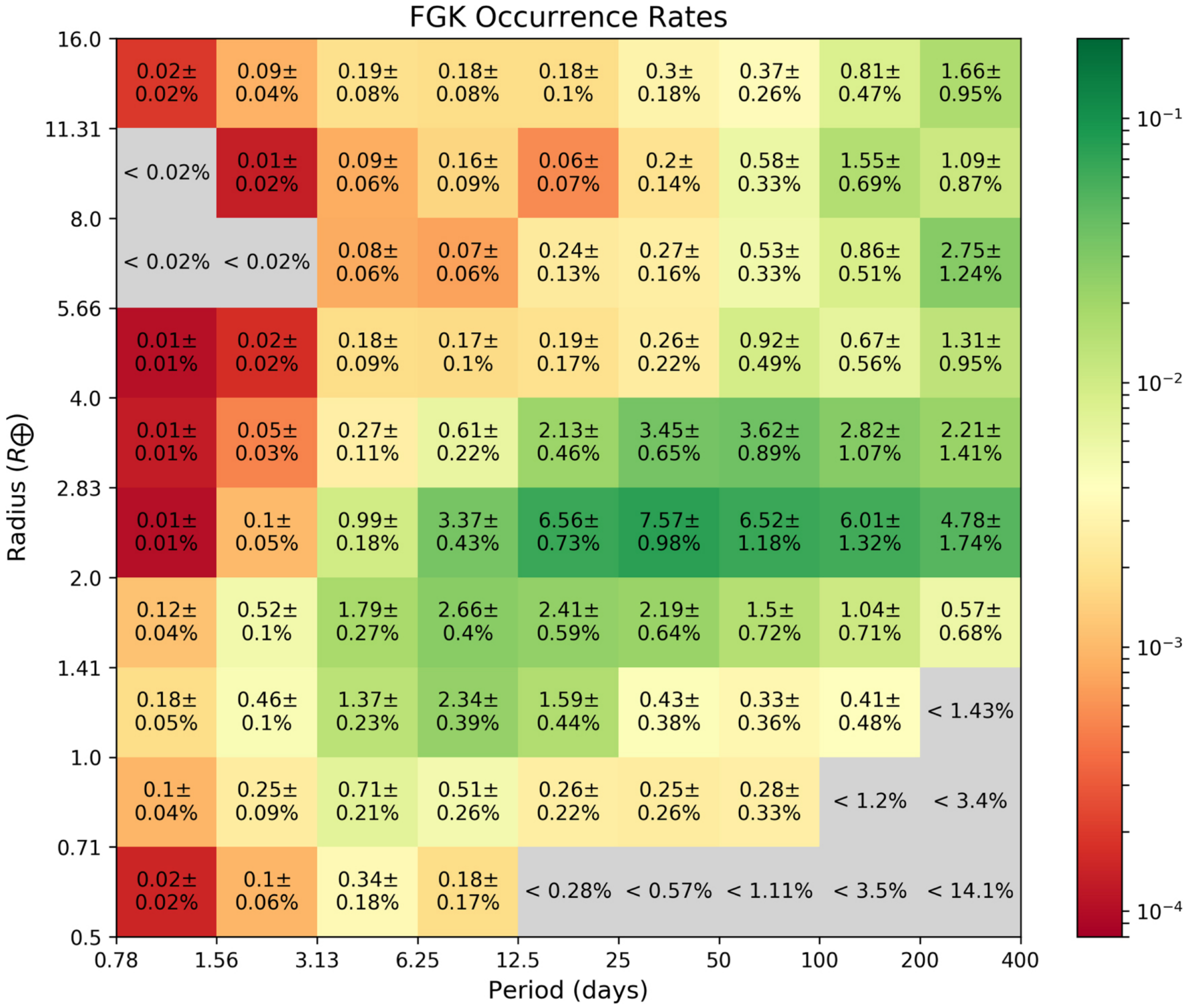
Properties of exoplanets

Surprise:
Hot Jupiters

Occurence rates in the picture are from Kunimoto & Matthews 2020.

Overall the exoplanet occurrence decreases with temperature of the star.


FGK Occurrence Rates

0.02± 0.02%	0.09± 0.04%	0.19± 0.08%	0.18± 0.08%	0.18± 0.1%	0.3± 0.18%	0.37± 0.26%	0.81± 0.47%	1.66± 0.95%
< 0.02%	0.01± 0.02%	0.09± 0.06%	0.16± 0.09%	0.06± 0.07%	0.2± 0.14%	0.58± 0.33%	1.55± 0.69%	1.09± 0.87%
< 0.02%	< 0.02%	0.08± 0.06%	0.07± 0.06%	0.24± 0.13%	0.27± 0.16%	0.53± 0.33%	0.86± 0.51%	2.75± 1.24%
0.01± 0.01%	0.02± 0.02%	0.18± 0.09%	0.17± 0.1%	0.19± 0.17%	0.26± 0.22%	0.92± 0.49%	0.67± 0.56%	1.31± 0.95%
0.01± 0.01%	0.05± 0.03%	0.27± 0.11%	0.61± 0.22%	2.13± 0.46%	3.45± 0.65%	3.62± 0.89%	2.82± 1.07%	2.21± 1.41%
0.01± 0.01%	0.1± 0.05%	0.99± 0.18%	3.37± 0.43%	6.56± 0.73%	7.57± 0.98%	6.52± 1.18%	6.01± 1.32%	4.78± 1.74%
0.12± 0.04%	0.52± 0.1%	1.79± 0.27%	2.66± 0.4%	2.41± 0.59%	2.19± 0.64%	1.5± 0.72%	1.04± 0.71%	0.57± 0.68%
0.18± 0.05%	0.46± 0.1%	1.37± 0.23%	2.34± 0.39%	1.59± 0.44%	0.43± 0.38%	0.33± 0.36%	0.41± 0.48%	< 1.43%
0.1± 0.04%	0.25± 0.09%	0.71± 0.21%	0.51± 0.26%	0.26± 0.22%	0.25± 0.26%	0.28± 0.33%	< 1.2%	< 3.4%
0.02± 0.02%	0.1± 0.06%	0.34± 0.18%	0.18± 0.17%	< 0.28%	< 0.57%	< 1.11%	< 3.5%	< 14.1%

Occurrence rate of hot-Jupiters in solar mass stars is about 1% (Marcy et al. 2005) but it drops significantly for lower mass stars. Based on TESS data and EGP ‘candidates’: 0.19+-0.07% for 0.088<Mstar<0.71Msol, 0.6<Rp<2Rj, 1<P<10d (Bryant et al. 2023). It is in agreement with core-accretion scenario for M>0.5Msol but in conflict for Mstar<0.5Msol where prediction is zero (Burn et al. 2021).

Properties of exoplanets

Surprise: super-Earths and sub-Neptunes are common

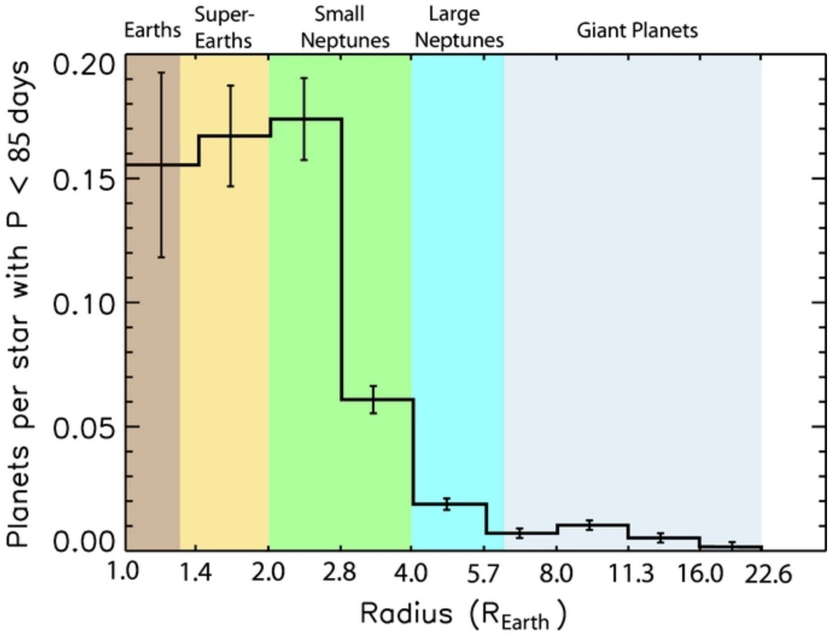
Based on Kepler planets:

An average number of planets around Sun-like stars is >1.

Fraction of stars with at least 1 planet is 45-100%.

Nearly every Sun-like star has a super-Earth or mini-Neptun (Fressin et al. 2013, Petigura et al. 2013, Mulders et al. 2018)

Average number of planets per size bin for main-sequence FGKM stars. Fressin et al. 2013 based on Kepler Q1-Q6.

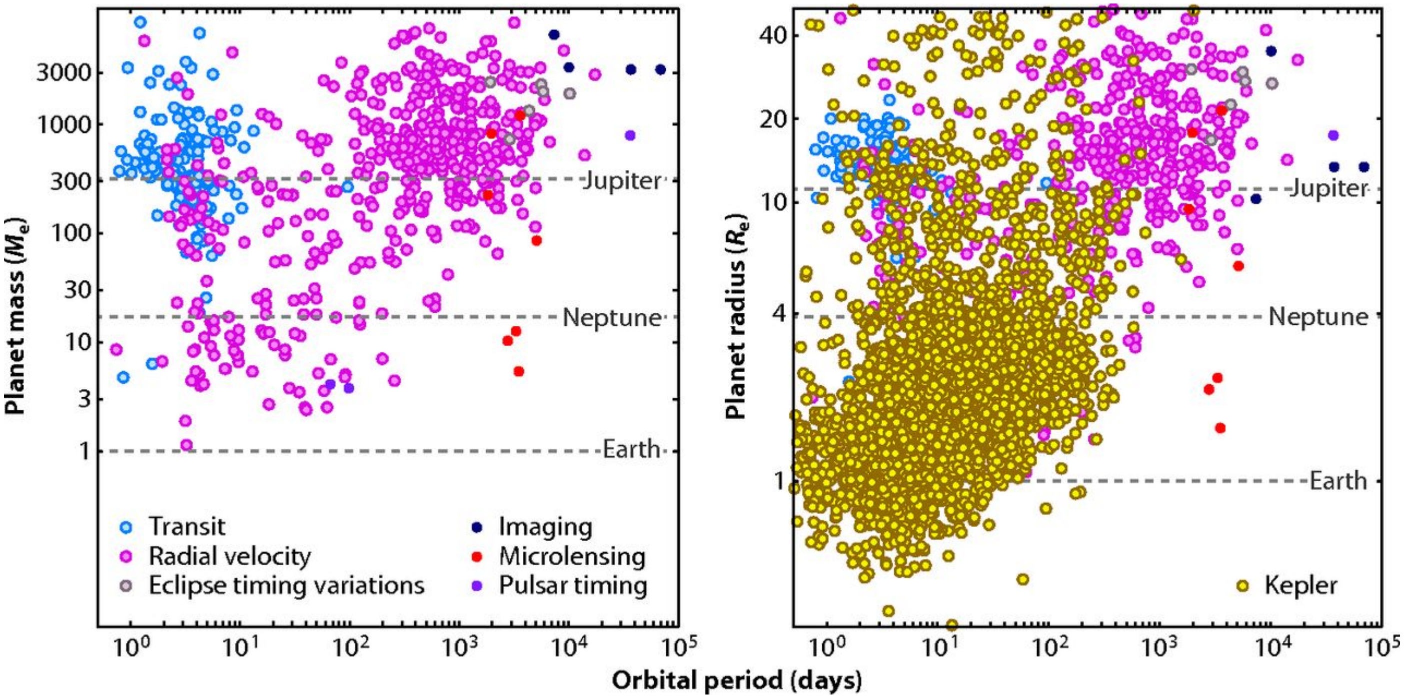


Properties of exoplanets

Surprise: Mass vs. separation

- Surprise: a number of Jupiter mass objects at a<0.1AU called hot Jupiters (Solar system does not have Hot Jupiters), should form beyond the snow line->migration
- There is a number of warm super Jupiters but a real lack of super Jupiters at a<0.5AU

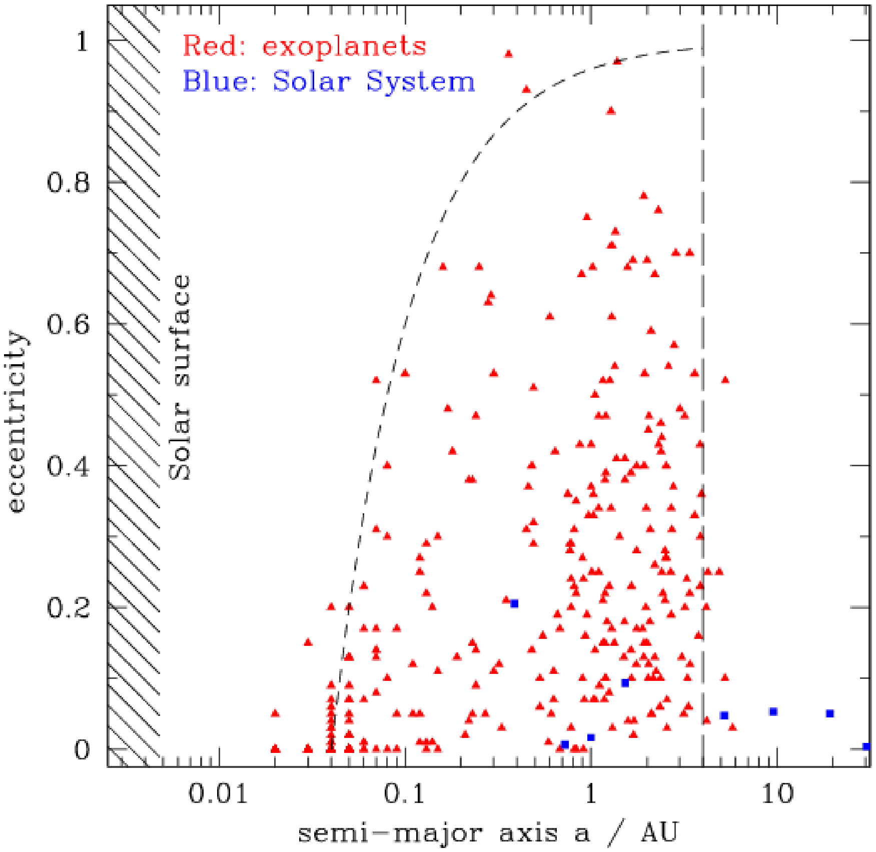
- Short period Neptunian desert for P<2-4 d (Szabo&Kiss2011, Neptuns have shallower potential well then Jupiters => intense evaporation or Roche lobe overflow, stop in migration depending on the disk hole correlating with the planet mass?)
- Strong selection effects (3m/s rv precision) and msini<20Mj arbitrary limit of the catalogue
- Brown dwarf desert: lack of companions with 10-80MJ around solar type stars



Left: non-Kepler planets (minimum mass)
Right: Kepler added (mass of non-Kepler converted to radius)
Batalha 2014, Seager&Bains 2015.

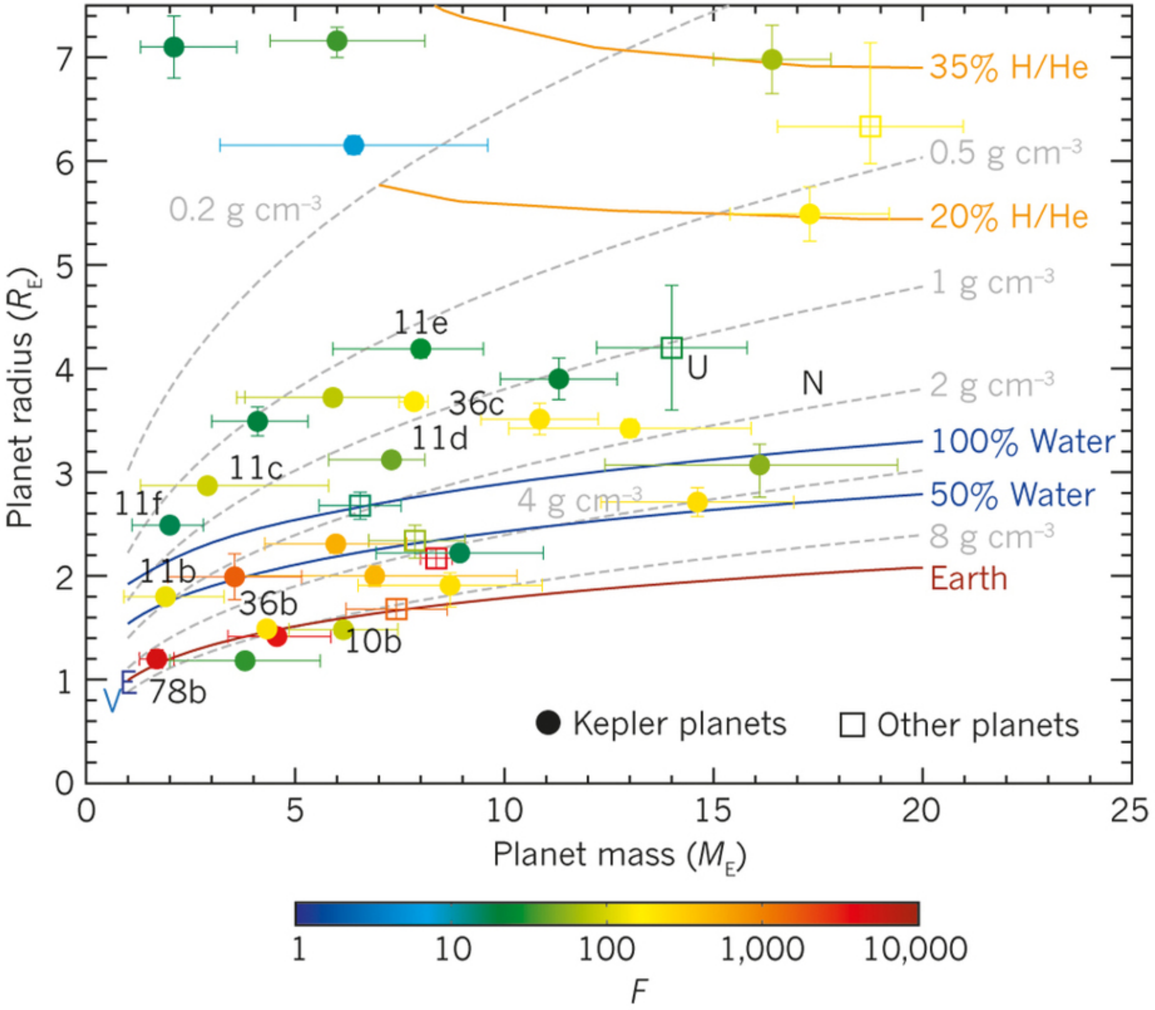
Properties of exoplanets

Surprise:
Eccentricity of giant exoplanets



- Solar system planets have e<0.1 except of Mercury
- Surprise: exoplanets with a>0.1 AU have various eccentricities (very few solar system analogues)
- For a<0.1AU eccentricities are much smaller and are tidally circularized
- Circular orbit of Jupiter may have important consequences on the orbits of other planets and the life on Earth
- 10% of stars have warm Jupiter, 1% of stars have a warm Jupiter on circular orbit so solar system is very unusual

Properties of exoplanets

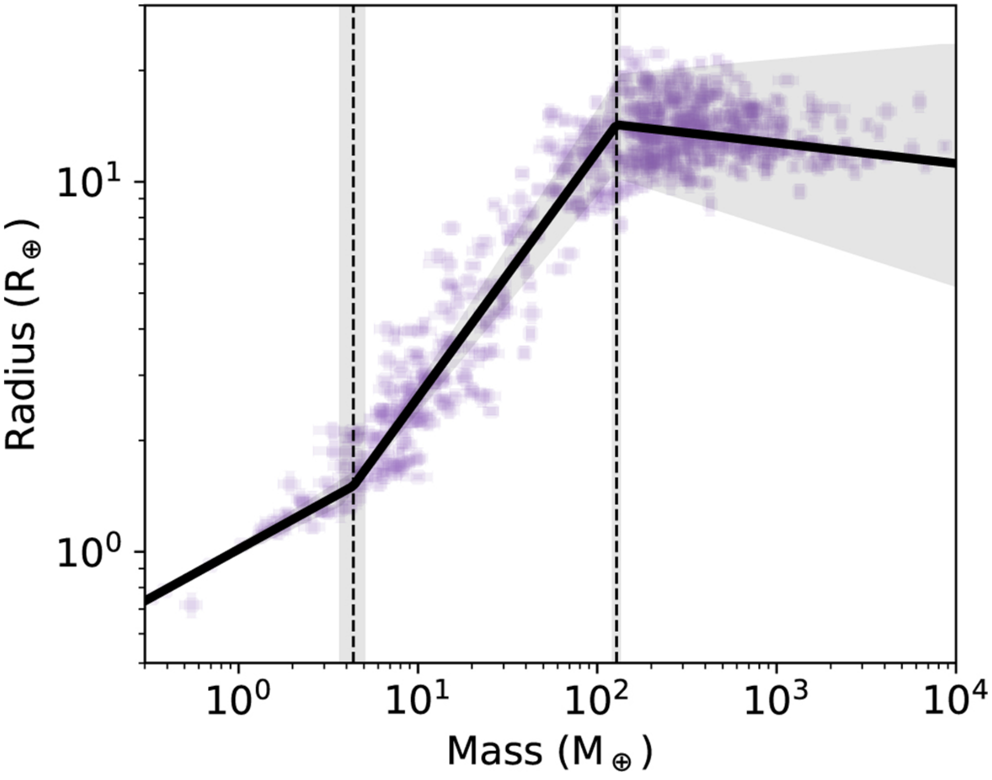


Mass-Radius relation

Can be used to estimate the planet composition but the same radius can be reproduced by different mixture of solids, ices & H,He gas (composition degeneracy).

Lissauer et al. 2014, Solid lines -composition of an envelope atop of a core of Earth like composition, Dashed lines -density, F- incident flux relative to Earth value, Full symbols- Kepler planets

Properties of exoplanets



Muller et al. 2024, based on 688 exoplanets with most precise parameters.

Mass-Radius relation

Planets can be divided into 3 groups:

-small=rocky, m<4Me, R<1.6Re, exponent is close to 1/3 of constant dens.

$$R \sim m^{0.27}$$

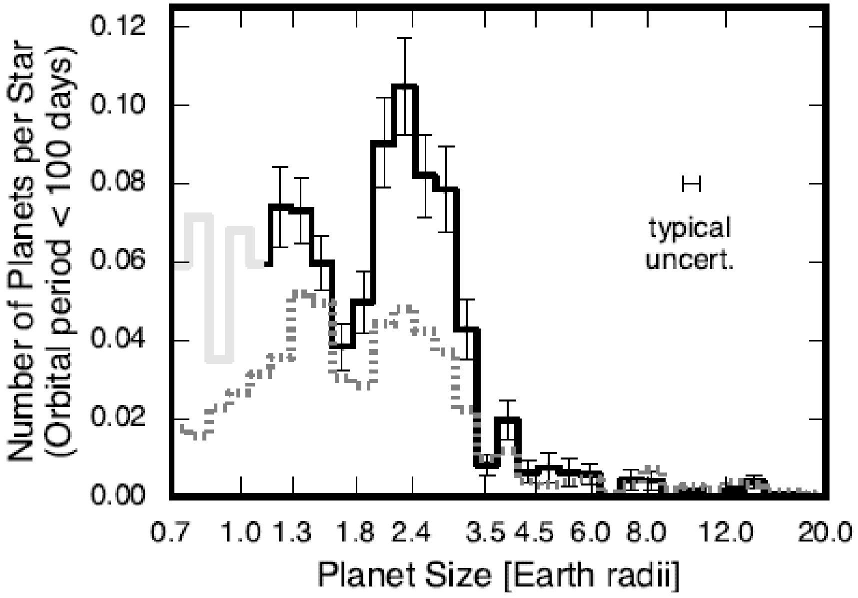
-intermediate, 4.4<m<130Me, R>1.6Re sub-Neptunes, small H-He envelope

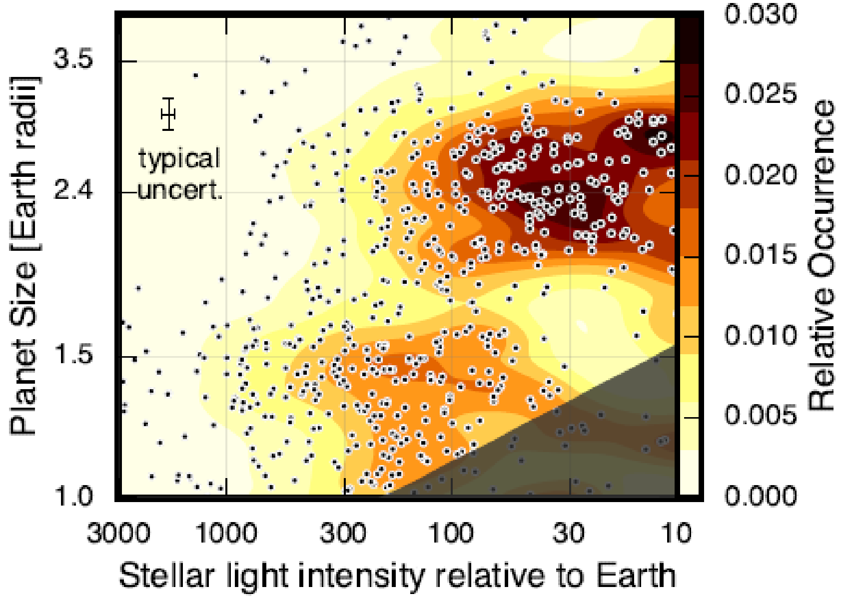
$$R \sim m^{0.67}$$

-giant, m>130Me=0.4MJ, H-He dominate, degenerate gas

$$R \sim m^{-0.06}$$

Properties of exoplanets





Radius valley

Surprise1: There is a rich population of super_Earth and sub-Neptunes at short periods not seen in the Solar system and not expected by contemporary theories

Surprise2: There is gap at 1.5-2.0 R_{Earth} called radius valley (sub-Neptunian desert at P<2d is also seen there)

Gap separates super-Earth from sub-Neptunes.

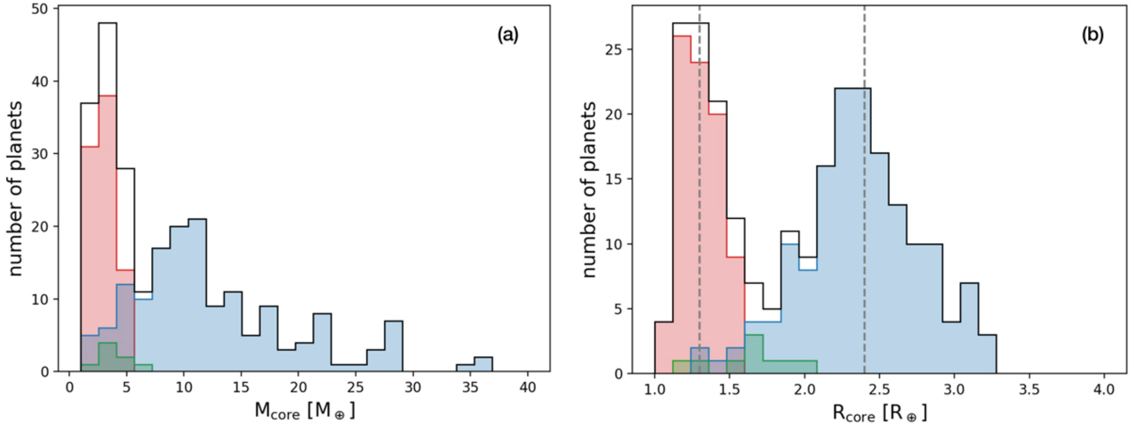
Fulton et al. 2017, Fulton & Petigura 2018, Kepler photometry + spectroscopic temperatures + GAIA DR2 paralaxes, No. of planets per star is also per bin in the planet radius.

Radius valley explanation

1/Evolution model:
A/Radius valey caused by the mass loss due to X-ray+UV photoevaporation (Fulton et al. 2017)
B/ core powered mass loss (core cooling, Gupta & Schlichting 2020)

Super-Earth and sub-Neptunes have the same dry cores (rocky, no ice) and bulk composition.
Sub-Neptunes are super-Earths (pure cores) with a small amount of H,He that expands their radii significantly.

2/Formation model:
A change of disk properties at the ice line is the primary cause (Venturini et al. 2020).
Planets born inside the ice line are small dry planet cores. Planets born beyond the ice line grow quickly, have more massive and water rich cores. Both types of planets migrate to Porb<100d where they are observed.
Envelope accretion and evaporation may add/remove more or less material to the cores.
Super-Earth and sub-Neptunes may have different cores and bulk composition.
Super-Earths are dry & rocky but might have been born also beyond the ice line and lost all H-He-H2O by evaporation.
Sub-Neptunes are wet, often 50-50 ice-rock + <10% H-He.



Venturini et al. 2020 (formation model), plane core masses (left), radii (right) after the formation and migration to P<100d.
Red=dry, blue= >45% of ice. Vertical lines = location of peaks from Fulton et al. 2017.

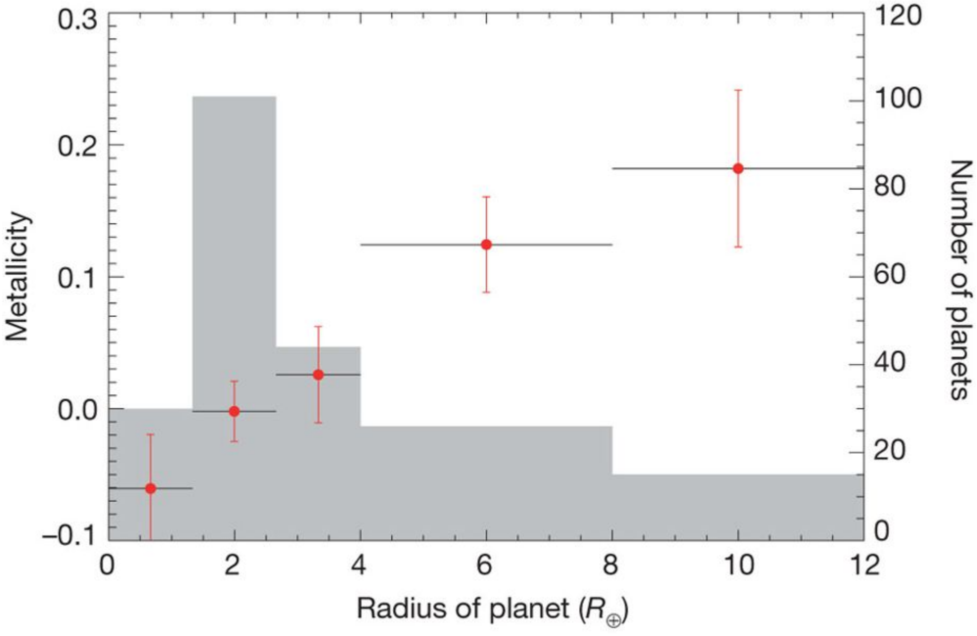
Properties of exoplanets

Metallicity

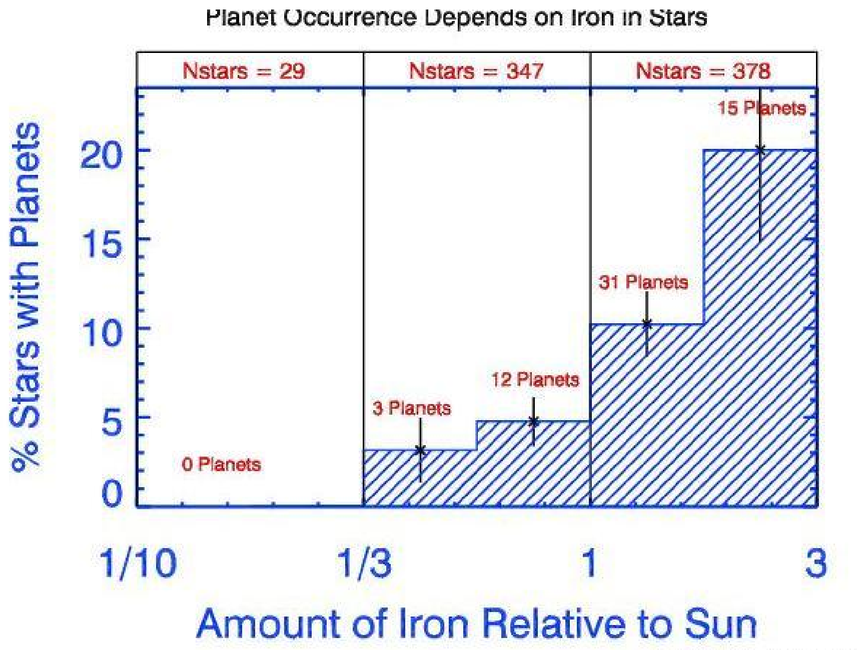
- Probability that the star hosts the planet depends on the metallicity of the host star.
- Larger planets & gas giants are more likely found around metal-rich stars. Smaller planets are found at wide range of metallicities (Fischer & Valenti 2005, Buchhave et al. 2012)
- This is in agreement with the core nucleation and accretion model

What is metallicity?

$$[M/H]=\log(N_m/N_H)_{Star}-\log(N_m/N_H)_{Sun}$$



Buchhave et al. 2012, dots=metallicity, grey histgr =No.of pl.



Fischer & Valenti

Properties of exoplanets

A fraction of transiting hot Jupiters (8:26) show significant projected spin-orbit misalignment and 5:26 have even retrograde orbits => challenge for planet formation and migration theory. One possibility is disturbances by other planetary or stellar companions. Picture: stars are shown to scale, colors are realistic, exoplanets are shown during the transit just before mid-transit. The last object at the lower right is for comparison and has a "normal" orbital direction. Triaud et al. 2010, AA, 524, A25

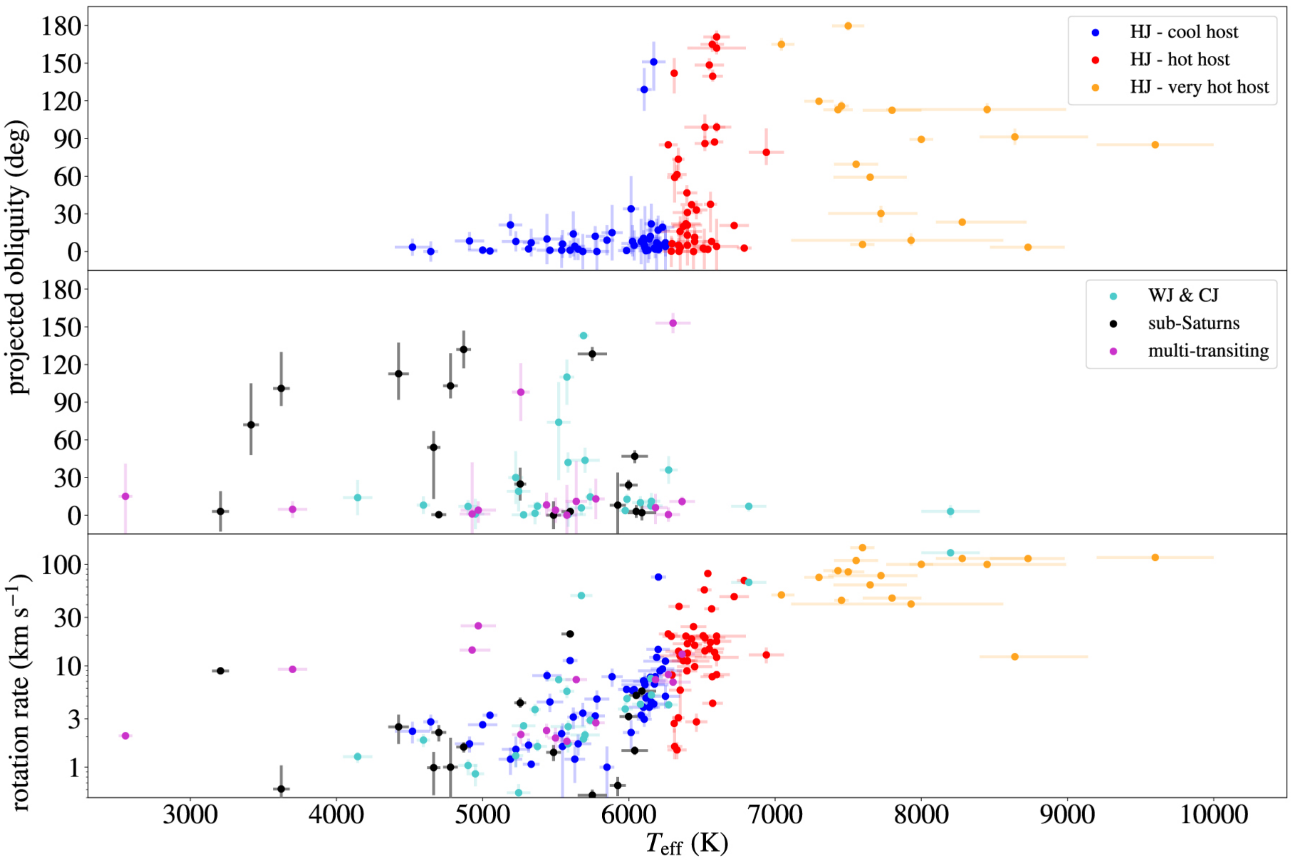
Surprise:
retrograde orbits
(wrong-way planets)
Obliquity=an angle between rotational axis of the star and normal to the planet orbit

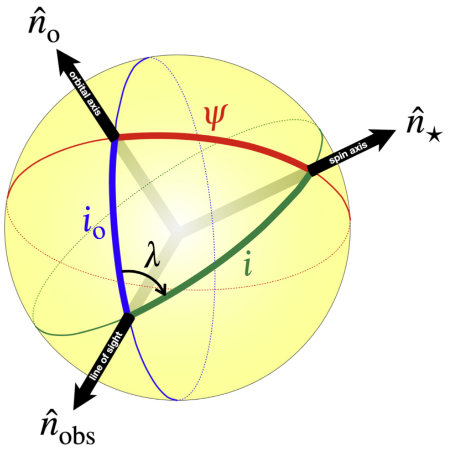
ESO (2010, April 13). Turning planetary theory upside down: Nine new exoplanets found, some with retrograde orbits. ScienceDaily.

Properties of exoplanets

The risk factors for a star with a close-orbiting giant planet to develop a high obliquity are a stellar mass exceeding about 1.2 M☉ or an effective temperature exceeding 6250 K. For cool stars also a relatively low planet mass (Neptunian instead of Jovian), and a relatively wide orbit ($a/R \gtrsim 10$).

It is likely associated with the changes in the internal structure, convection (stars M<1.3Msol have radiative core, M>1.3Msol=convective core), rotation, age. An early misalignment (scattering, Kozai, warped disks) is likely followed by tidal damping of obliquities,

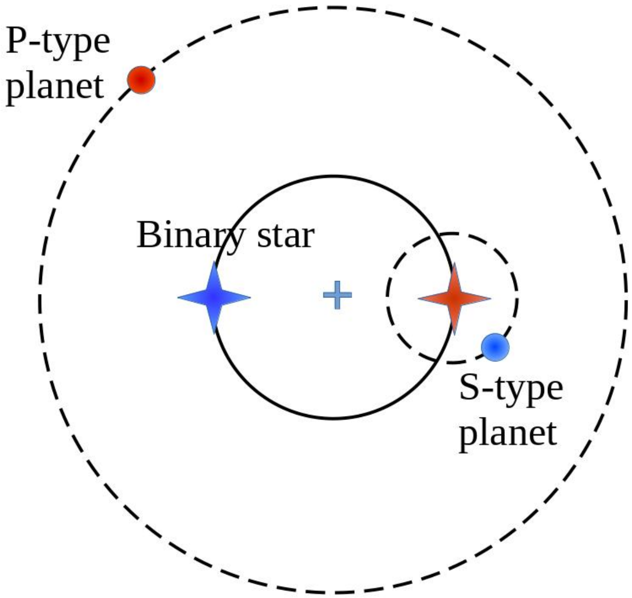




Albrecht et al. 2022,
i0-inclination of the orbital axis,
i-inclination of the rotational axis,
Ψ-obliquity,
λ-projected obliquity

Exoplanets in binary systems

- Important since most of the stars (except red dwarfs) are in binaries.
- S-type planets (Satellite type, Single star): planets orbiting a star that are closer than the secondary star. These are mainly planets in wide binary star systems where the star-star separation is more than 10x planet-star distance. They are quite common (812 multiple stars with S-type planets known as of Oct 2025).
- P-type planets (Planetary type, Pair): planets orbiting a central binary star also called **circumbinary** planets. They are rare (only about 35 P-type planets as of Oct 2025) and difficult to detect by RV since the stars are moving with high amplitude around the center of mass.



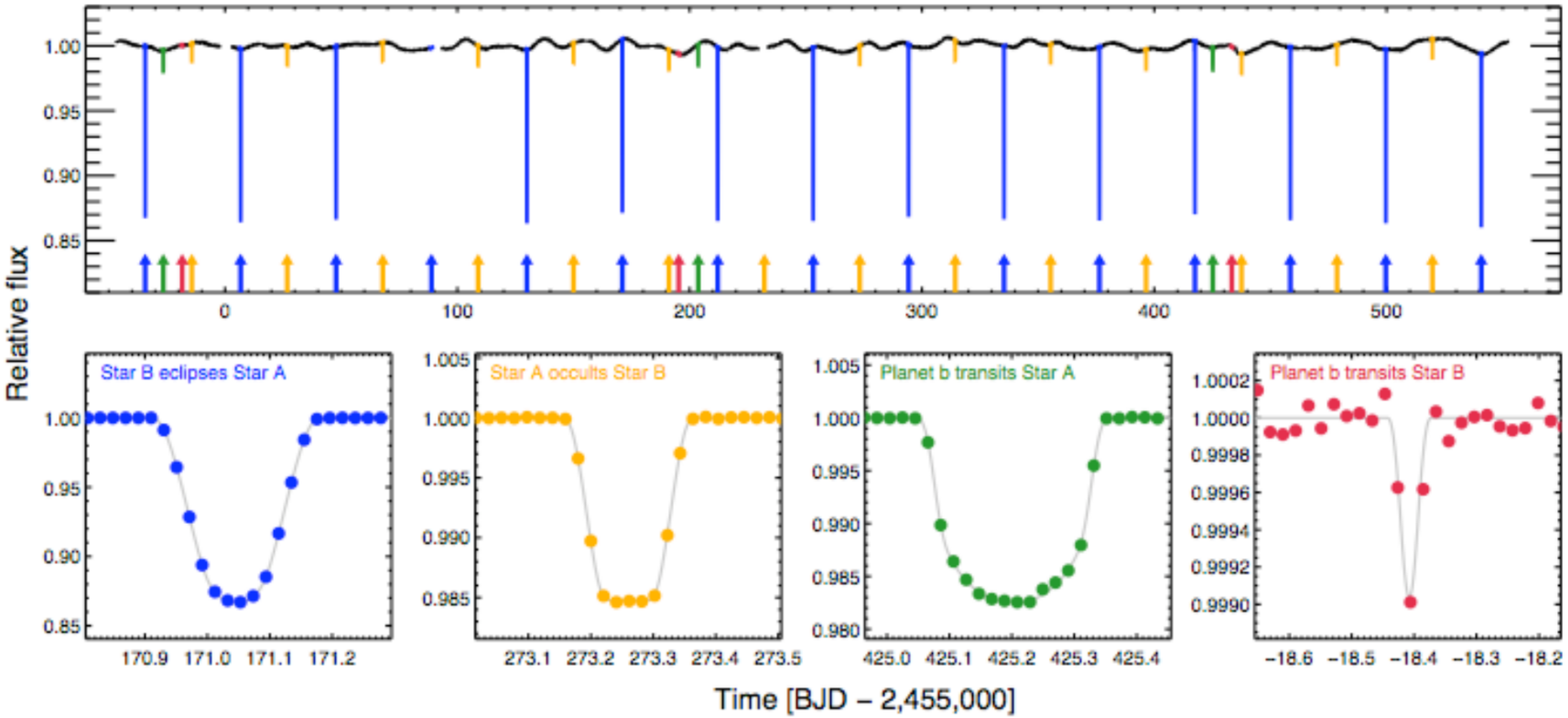
CircumBinary exoplanets

are planets orbiting a binary star

- PSR 1620-26([millisecond pulsar+WD]=191d, Backer et al. 1993). The first CB planet, detected by pulsar timing. M=2.5M_J, P=100yr.
- Kepler 16b (Doyle et al. 2011) the first CB planet orbiting an eclipsing binary made from normal MS stars (Porb=41d, elliptical). It is a transiting Saturn mass planet (Porb=229d, circular). Planet transits both stars, exchanges momentum with the binary, transits are irregular, variable timings & duration. Precession => transits stopped and will resume in about 20yr.
- Porb(pl)<4.5Porb(star) orbits are unstable. This also means that the protoplanetary disk is truncated here, which stops migration and planets accumulate at the edge of the disk.
- Eclipsing binaries: high incidence of circumbinary planets due to orbit alignment and precession. Even most of the planets detected by RV will transit at some point due to precession.
- Detection with eclipse timing, radial velocities.

Kepler 16b. During the transit the stars are moving behind the planet rather than planet in front of stars, Doyle et al. 2011

Circumbinary exoplanets



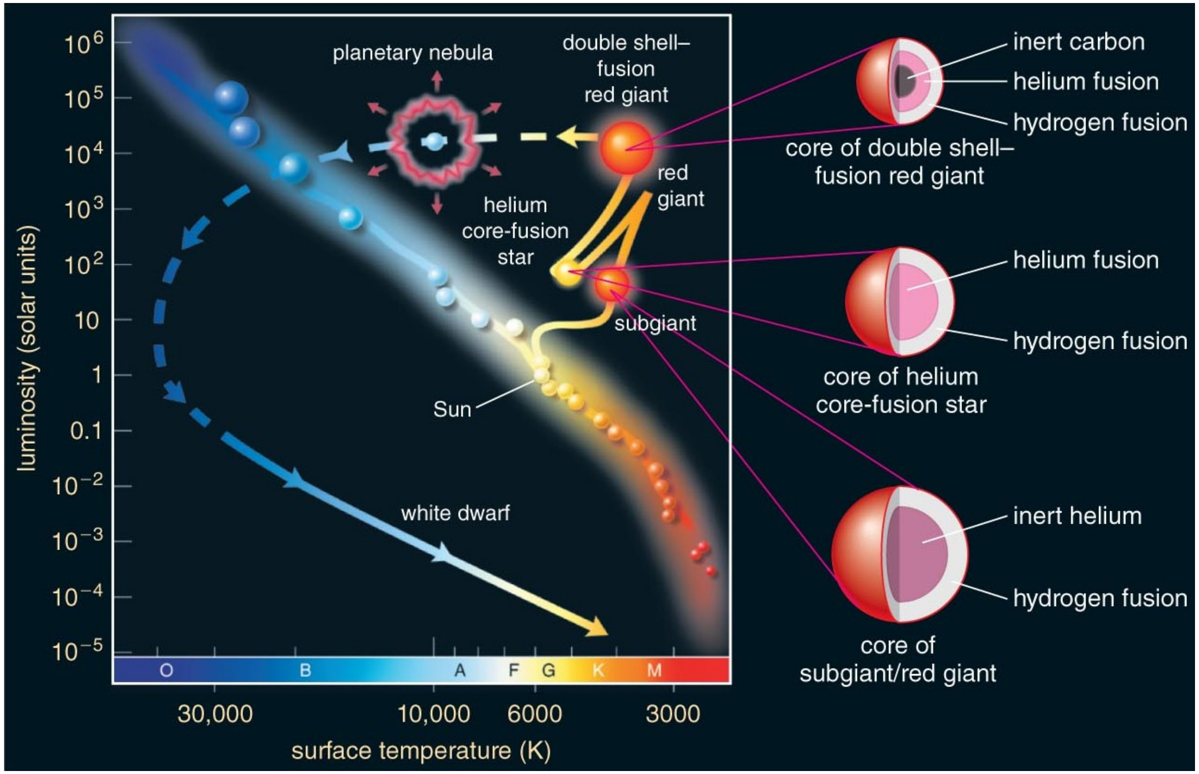
Kepler lightcurve of Kepler 16b, Doyle et al. 2011.

Blue: primary eclipse (StarA is hotter and bigger than StarB), yellow: secondary eclipse (shallower, total, shorter due to eccentricity), green: planet/StarA (deeper than yellow, long since both objects are slow), red: planet/StarB (very shallow and short since StarB is cool and fast).

AGB stars and PN

AGB star -late evolution stage of 0.5-8 Msol mass stars. They are quit common and often in binaries. Stars expand and loose significant fraction of their mass via a slow wind and thermal pulses. The core of AGB star becomes a hot white dwarf that ionizes the envelope creating a planetary nebula. If in a binary system, AGB star engulfs the secondary creating common envelope, stars spiral together, envelope is ejected. Endproduct is short period post-common envelope binary with a white dwarf or a hot-subdwarf and a possible planetary nebula (PN).
PN is a misnomer (W.Herschel 18century) and has nothing to do with planets. PNe are big (1ly) with a very low density (100-10^4 particles/cm^3), forbidden emission lines [OIII]5007.

Cat’s eye nebula (Credit: NASA/HST)

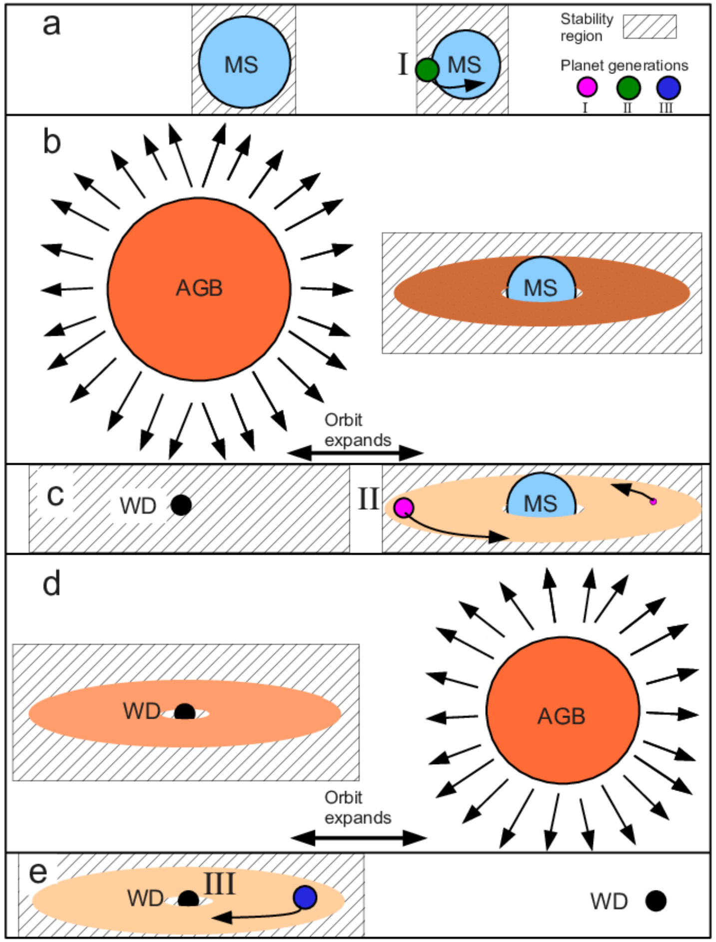


© Cosmic Perspective Fig 17.8, https://jila.colorado.edu/~ajsh/courses/astr1200_18/starevol.html

2-nd generation planets

Since the discovery of first exoplanets orbiting close to a pulsar (Wolszczan & Frail 1992) it was debated that these exoplanets might have been born from the supernova ejecta. Such planets are called second generation (SG) planets. Massive stars are rare hence such SG planets will be rare.

Favourable conditions for SG planets are in binary stars in which one of the components passed via AGB stage. Primary (more massive) star lost a significant fraction of mass that is now in a disk around the secondary or in a circumbinary disk. SG planets can be born there.
The secondary star can also pass via AGB stage in which case 3rd generation of planets can form.



Picture from Perets 2011.

Properties of exoplanets

Multiple planet systems

- Low-order (2:1,3:1,4:1) mean motion resonances (MMR) are observed
- Beyond 4:1 orbital period ratios stray from integer values
- For low-order MMR systems, the departures from the simple independent Keplerian fits to the orbits may be non-negligible
- Multiple planet systems have lower eccentricities than single planets
- Most planets: Kepler-90b-i, Sun (8), TRAPPIST1 (7), HD10180 (6+3?)...

Titius-Bode rule resurrected?

- 55 Cancri has 5 exoplanets with a=0.038, 0.115, 0.24, 0.781, 5.77, They obey a sort of T-B rule if we assume n=1-6 with n=5 missing

$$a=0.0142\ e^{0.9975n}$$

- This is a situation reminiscent of the solar system before the discovery of Ceres (Poveda & Lara 2008)

-A large fraction, 60-95%, of multiple systems are ‘packed’, which means that no other planet could be inserted (have formed), and survive in between two observed exoplanets (Obertas et al. 2023).

Definition of an extrasolar planet

Basic facts:

- Deuterium burning limit is 13 Mj, it is analogous to the H burning limit for sub-stellar objects
- Companions with the mass of 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

Exoplanet is:

- Object orbiting a star other than the Sun or a stellar remnant or a brown dwarf (no free floating planets)
- There is no precise definition but most researchers accept an object with m<13Mj or msini<13Mj
- Massive enough to satisfy constraints for planets in the Solar system
- Mass ratio < 1/25 (below L4,5 instability) added in 2018
- This definition is not final and will change

Terms & Naming conventions

There are many frequently used terms but are not strictly defined yet.

hot Jupiter – an exoplanet with 1<m<13Mj and hot, often a<0.1AU

Sub-brown dwarf = free-floating planet, m<13Mj

Earth-like planet – a planet with radius of 0.8-1.25 R_{Earth}

Super-Earth – a planet with radius of 1.25-2 R_{earth} (or with mass of 1-10M_{Earth})

Mini-Neptun (sub-Neptun) – has radius of 2-4 R_{Earth}

For single planetary companions to a host star, the name is generally NNN b where NNN is the parent star name.

For multi-planet systems, the planet names are NNN x, where x = b, c, d, etc. refers to the chronological order of discovery of the planet.

If more planets are discovered at the same time then the order b,c,d... is with increasing a.

Planet around B component of the binary star is NNNBb.

Circumbinary planets:? HW Vir(AB)b

Exceptions are possible, like WASP-12b, Kepler-90i or planets detected by microlensing.

For "free floating" sub-brown dwarfs, the name is given by the discoverers.

IAU initiative to name exoplanets is mainly for public and not used by professionals.

Exoasteroids: WD1145+017

-WDs enable detection of small objects

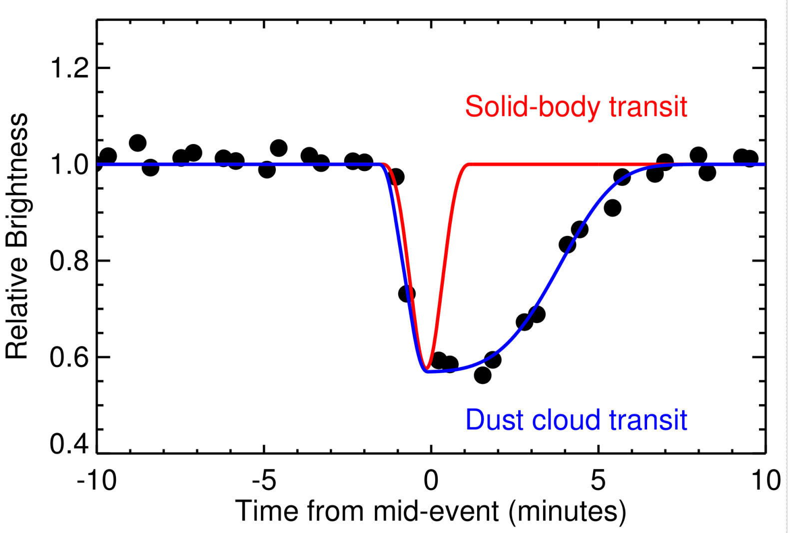
$$\Delta F \approx \left(\frac{R_p}{R_s}\right)^2$$

-Vanderburg et al. 2015 from K2 data, transit-like variable asymmetric signal, P=4.5h, dust tail transits

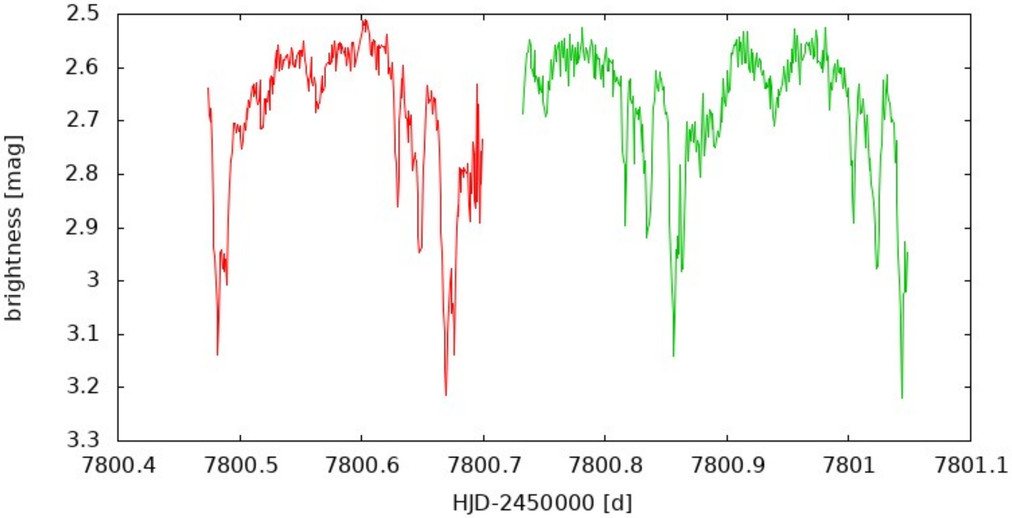
-light curve evolution, disintegration, many bodies with similar periods

-IR excess → Dust disk

-broad circumstellar lines -> gas disk



Vanderburg et al. 2015



Maliuk et al. in preparation

WD1145+017

Surprise:
chemical composition of the star is very similar to CI chondrites but C, N, S are underabundant and almost identical to bulk Earth composition

How is it possible?

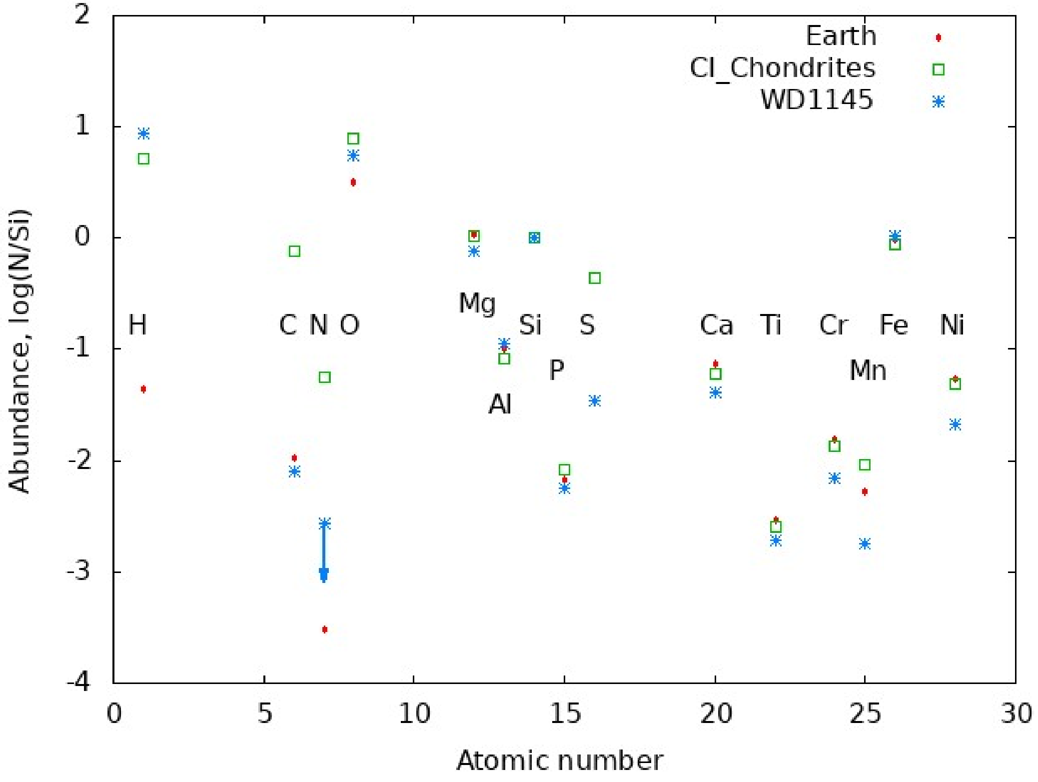
-some WDs have IR excess and 1/4-1/2 of WDs have metal lines. They are called DZ type WDs

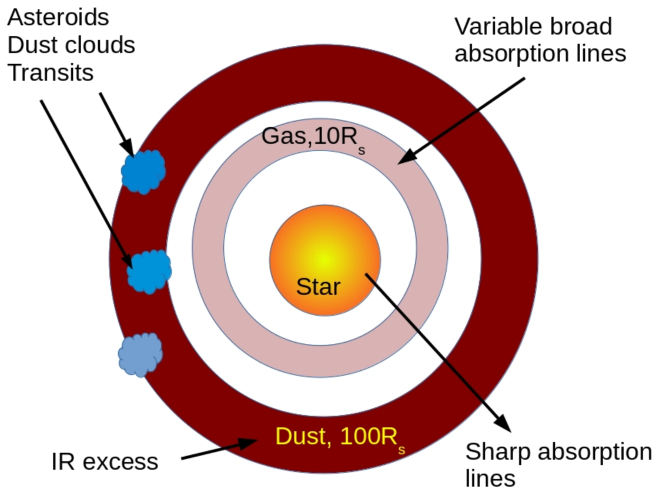
-problem: metals should not be there and should have sunk quickly because WDs have gravity 10^4 times higher than on the Sun

-hypothesis (Debes&Sigurdsson 2002, Jura 2003): perturbations of planetary orbits during AGB mass loss phase -> closer orbits -> tidal disruption -> accretion -> DZ WD

-WD1145 is the first WD to be orbited by exoasteroids, a direct proof of that hypothesis. We see it all happening in front of our eyes: asteroid, its disintegration, dust cloud, gas disk, and chemical composition....

Budaj, Maliuk, Hubeny 2022, A&A 660, A72

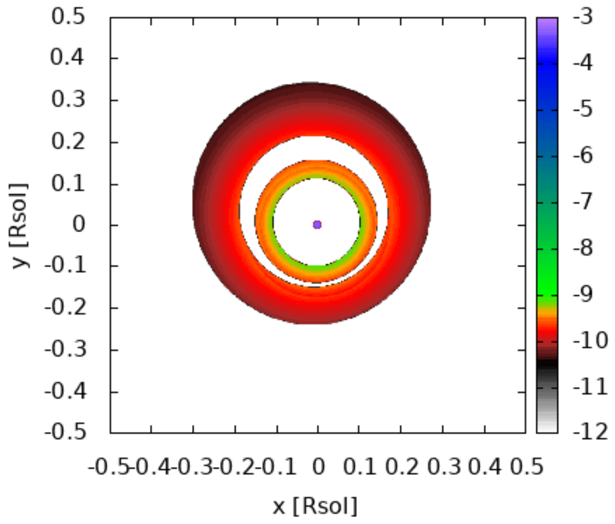




WD1145+017

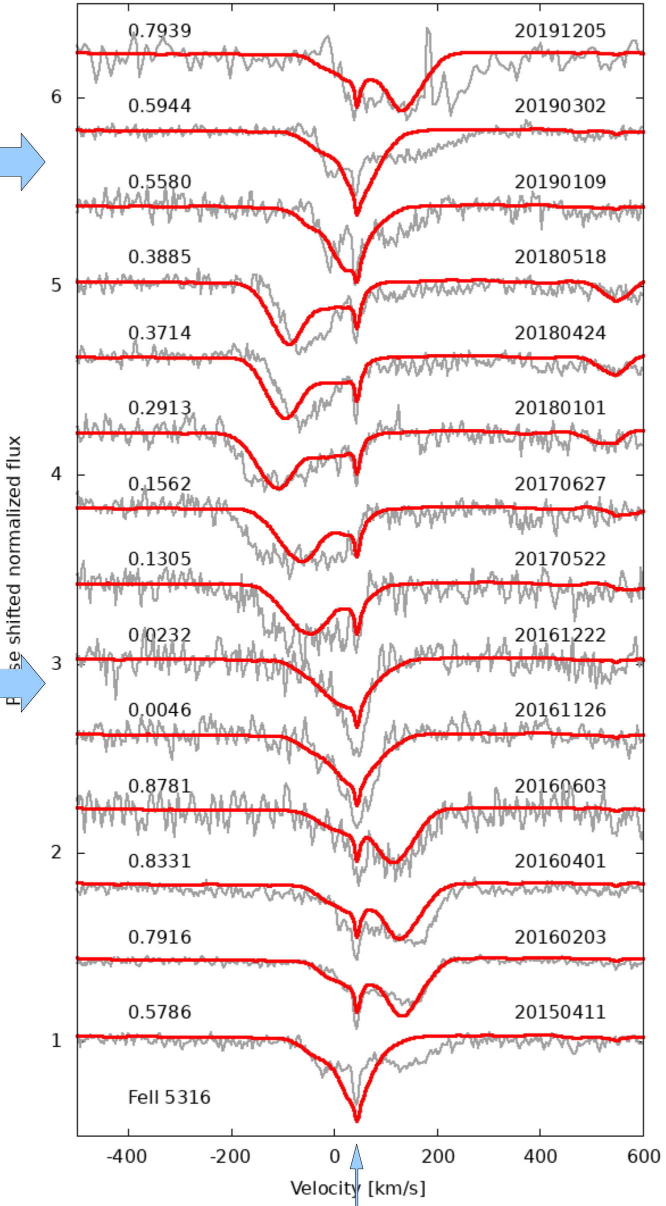
Budaj, Maliuk, Hubeny 2022, A&A 660, A72

2 elliptical disks:
-chem. composition=atmosphere but no He
-inner, hotter, circular disk, e=0.06, p=10-14Rs
-outer, cooler, elliptical disk, e=0.18, p=15-24Rs
-inclination=90deg
-GR causes prograde precession P=3.83 yr
which causes line variability



periastron

apoastron

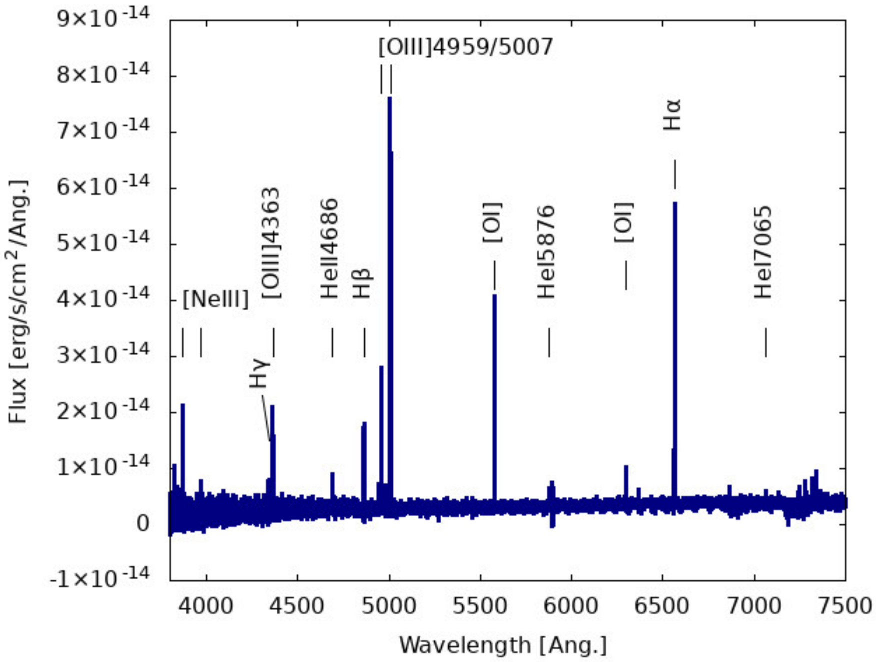


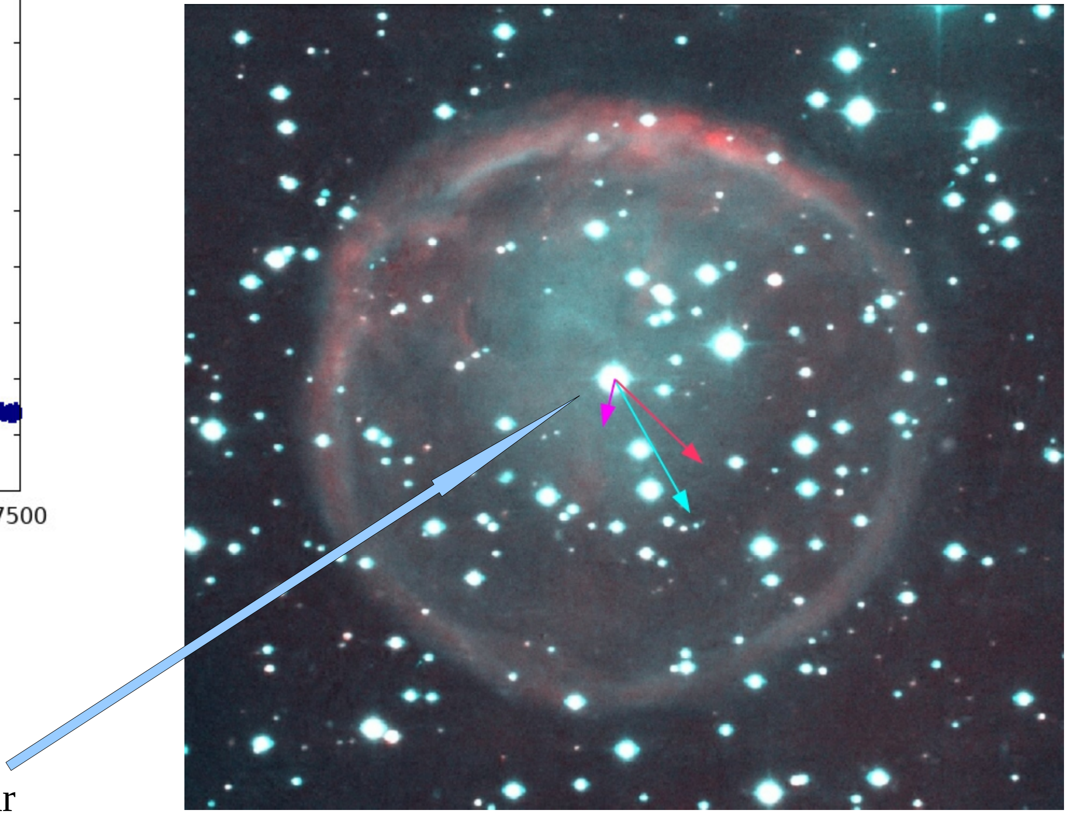
Star with gravitational redshift

Dusty objects in planetary nebula WeSb1

WeSb1: PN discovered by
Weinberger & Sabbatin 1981

Planets have been detected around MS stars, RG and WDs. What happens with the planets between AGB and white dwarf stages? Spectrum and imaging from Budaj et al. 2025, Nature Astronomy,9,380

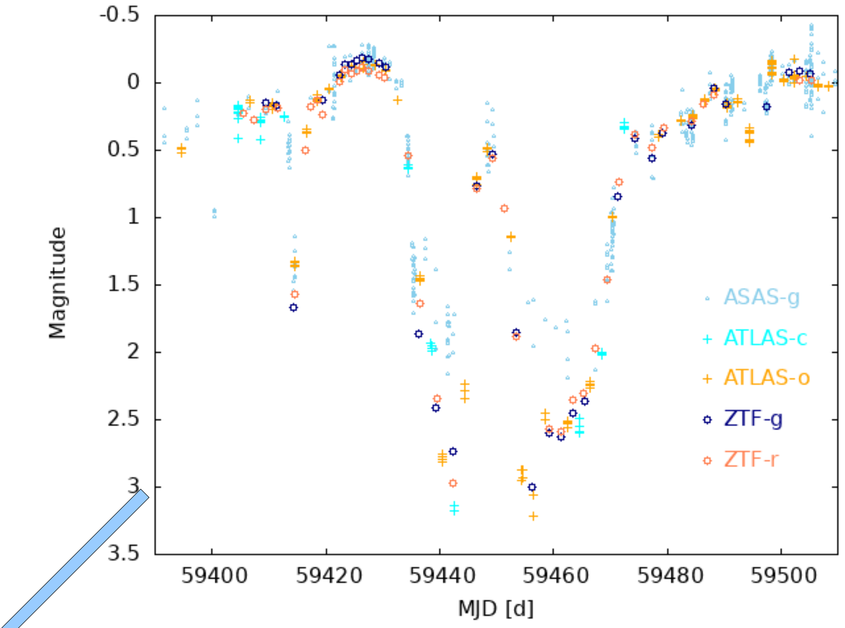


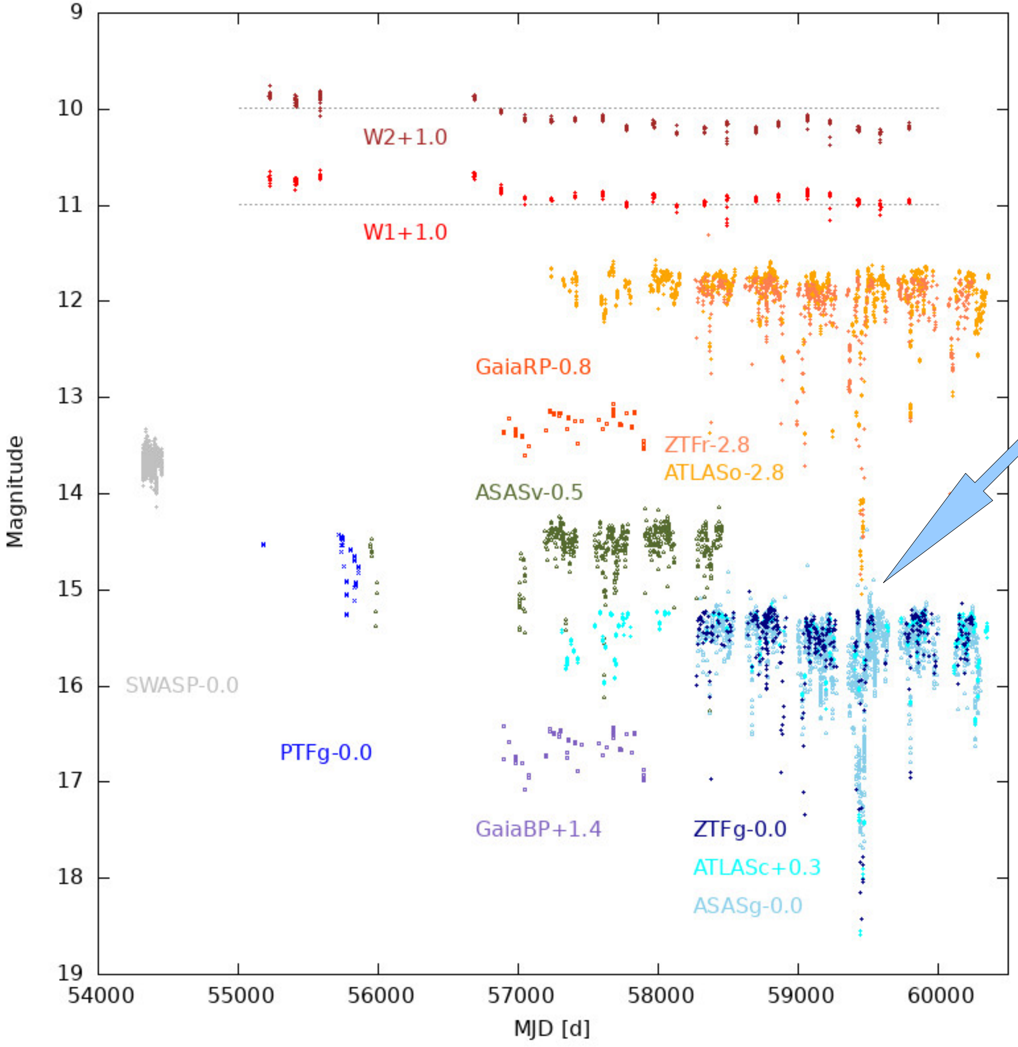


Central star

PN radius=1.6pc (5.4lyr)
PN kinematical age=80kyr
One of the largest and oldest PNe.

Dusty objects in planetary nebula WeSb1





It is a binary star composed of an F-subgiant and a hot CSPN (not seen).

Many dips seen in the optical → something is eclipsing/ orbiting F-subgiant or both stars.
Eclipses are deep and numerous → many large bodies >4 Rsol → dust clouds.

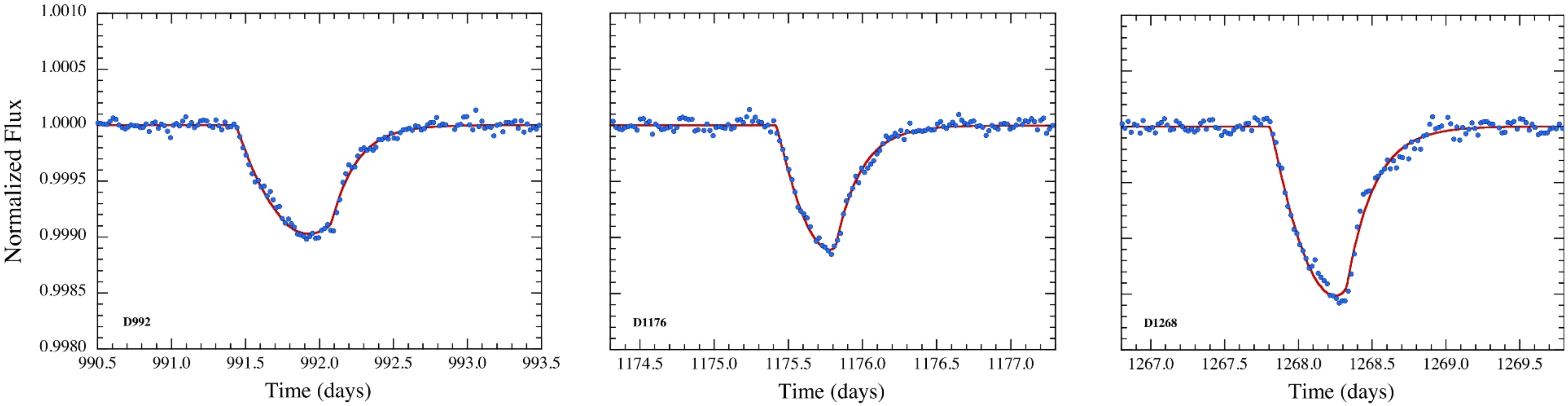
Dust clouds are likely a result of collisions between rocky bodies. Planetary systems undergo a violent evolution during the PN stage (Budaj et al. 2025).

Exo-comets

After exoasteroids even smaller extrasolar bodies were discovered (Rappaport et al. 2018) using Kepler
Star: 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

Comets could be efficiently ejected from the exo-Oort clouds of AGB stars, which loose most of their mass resulting to a weaker gravity (Veras et al. 2011). Hypothetical post-main sequence exocomets are referred to as Jurads (demons, Mike Jura).

Characteristic shape of comet transits. KIC3542116. Rappaport el al. 2018



Interstellar objects: Interlopers

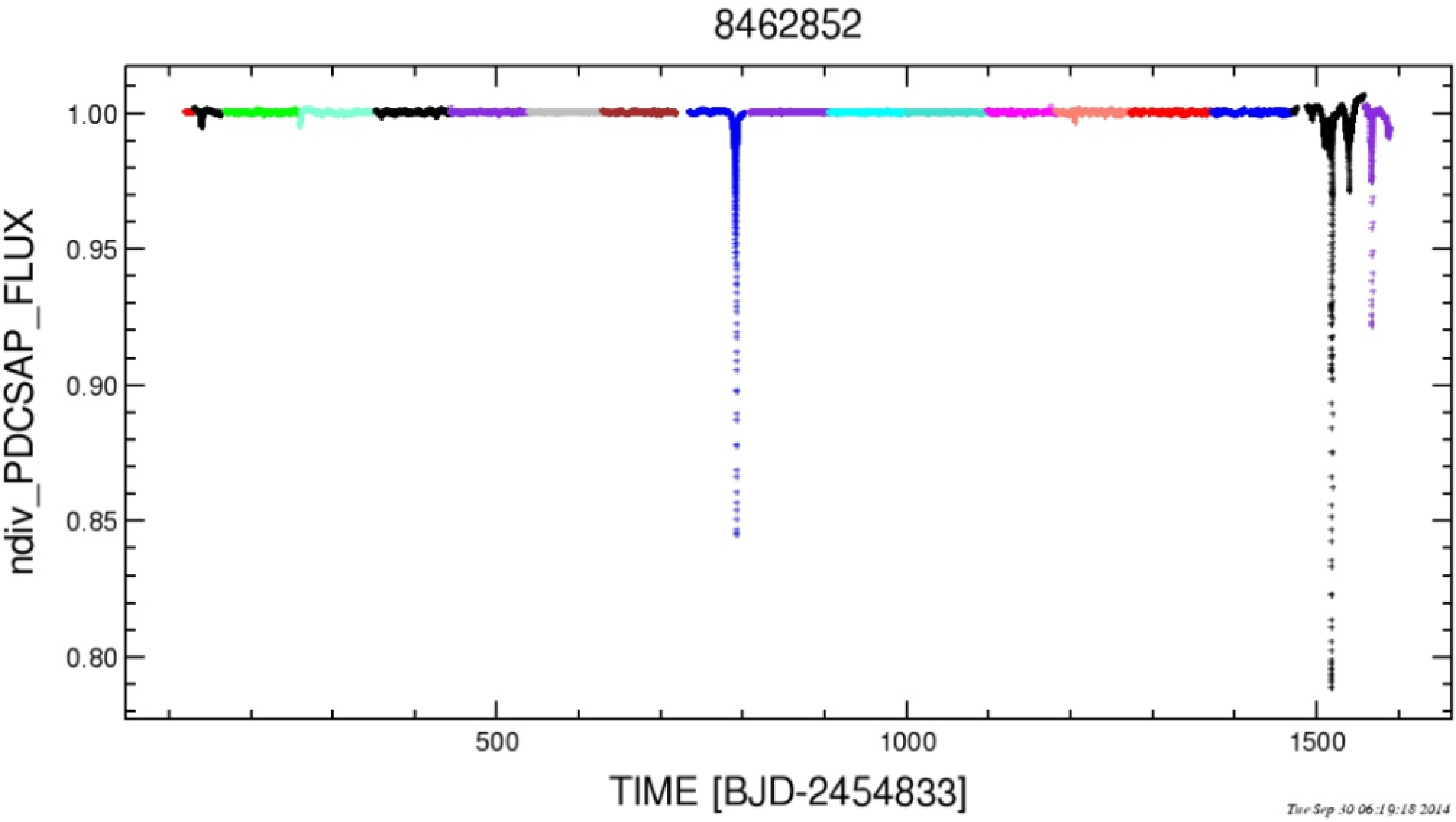
Interstellar Interlopers (interstellar objects in the solar system):

1I/’Oumuamua, exoasteroid (Williams et al. 2017, Meech et al. 2017), small 100-1000m, not a simple rotation, multiple periods P=7.3-8.1h, variable amplitudes 1.5-2.5 mag → extremely flat or prolongated, 10x longer than wider (artist’s impression below)

2I/Borisov, exocomet=interstellar comet (Borisov 2019), CO outgassing (formed beyond CO snowline) contrary to H2O dominated Solar system comets

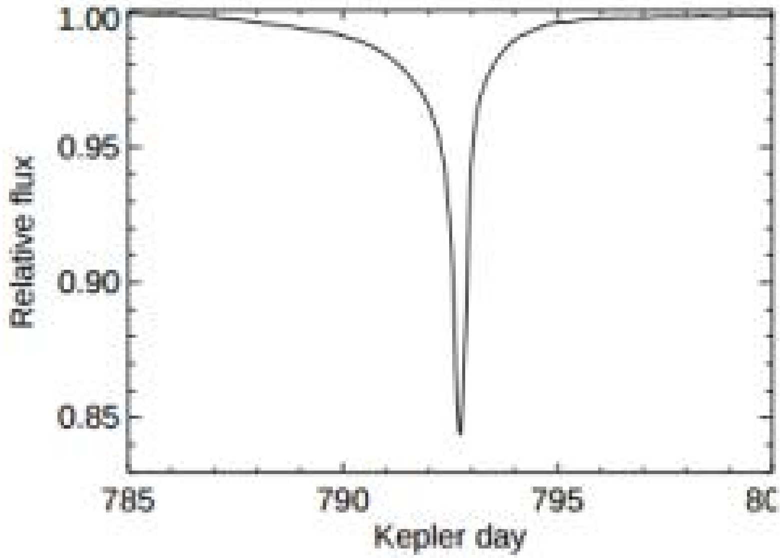
3I/ATLAS (Bolin et al. 2025), exocomet

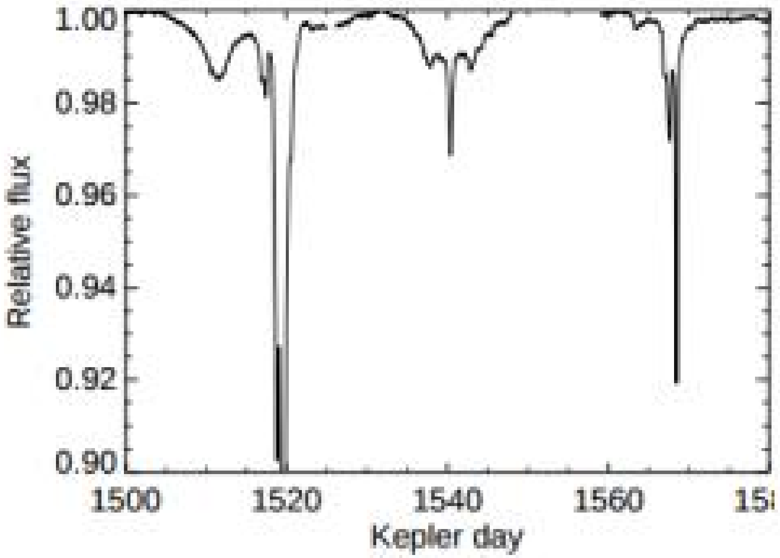
”Exo-ti”: KIC8462852 =Boyajian‘s star

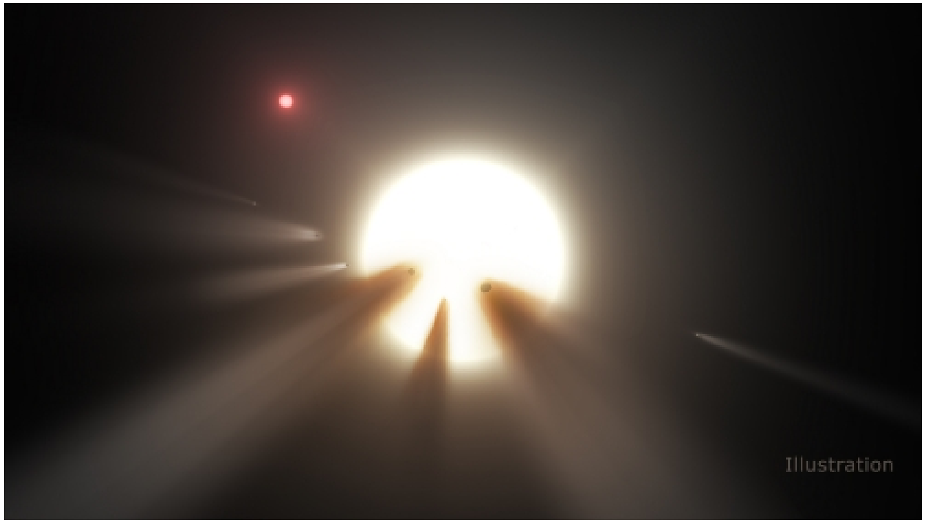


Boyajian et al.(2016), planet hunters, Kepler, V=12mag, sp. FV

”Exo-ti”: KIC8462







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Swarm of Comets

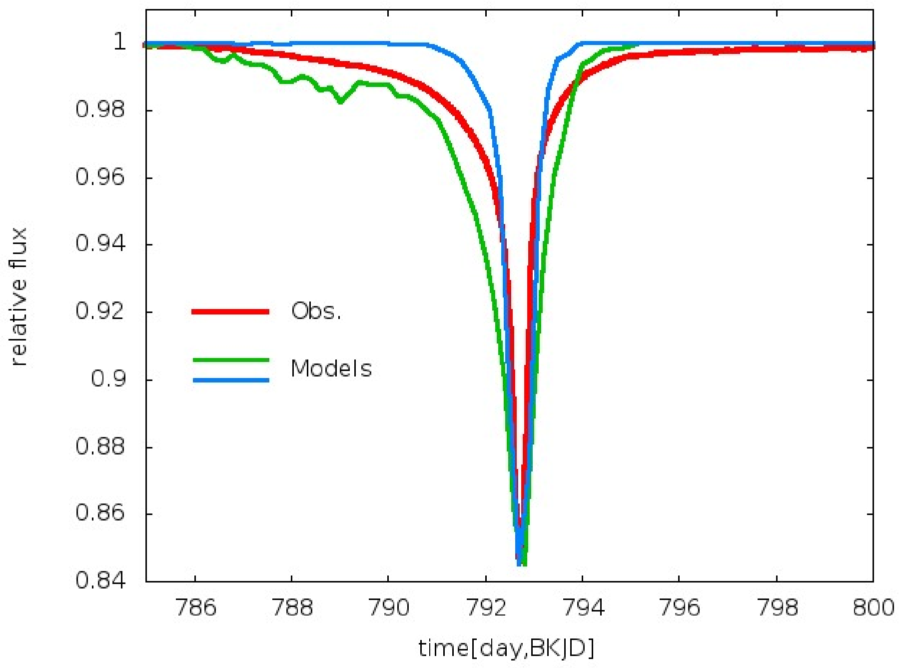
- Bodman & Quillen (2016)
  - a swarm of 70-700 comets
  - highly eccentric orbits
- Pros:
  - Fits most of the features very well
  - Satisfies the IR limits
  - Such comets are known to exist and have high probability of transit
- Cons:
  - cannot reproduce smooth 800d feature
  - produce shallower 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

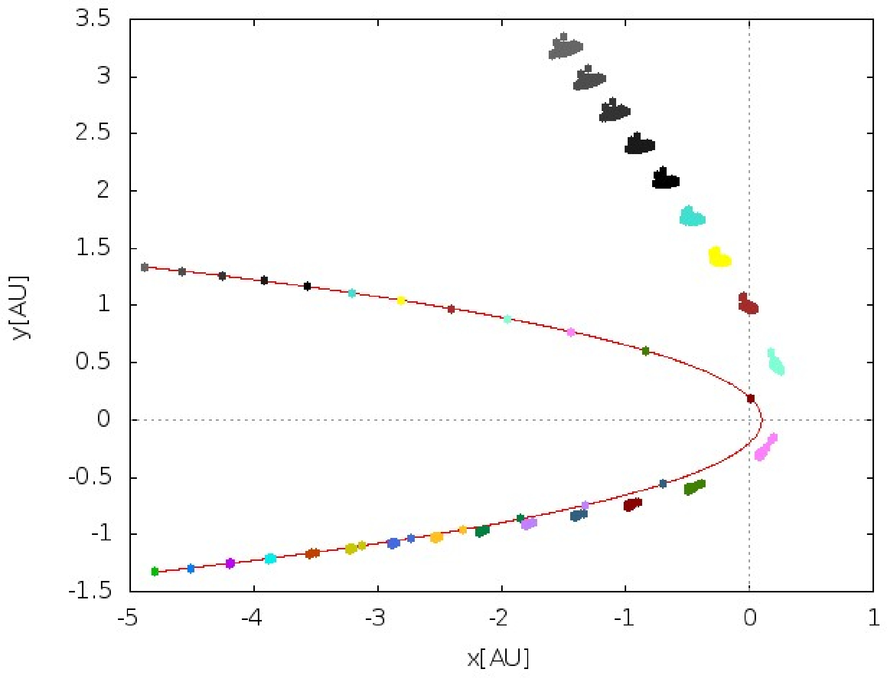
Massive bodies wrapped in the dust

- Neslusan & Budaj (2017)
- star & 4+ massive bodies with dust clouds
- Assumptions: initial dust cloud model, gravity (star+body), P-R drag
- 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

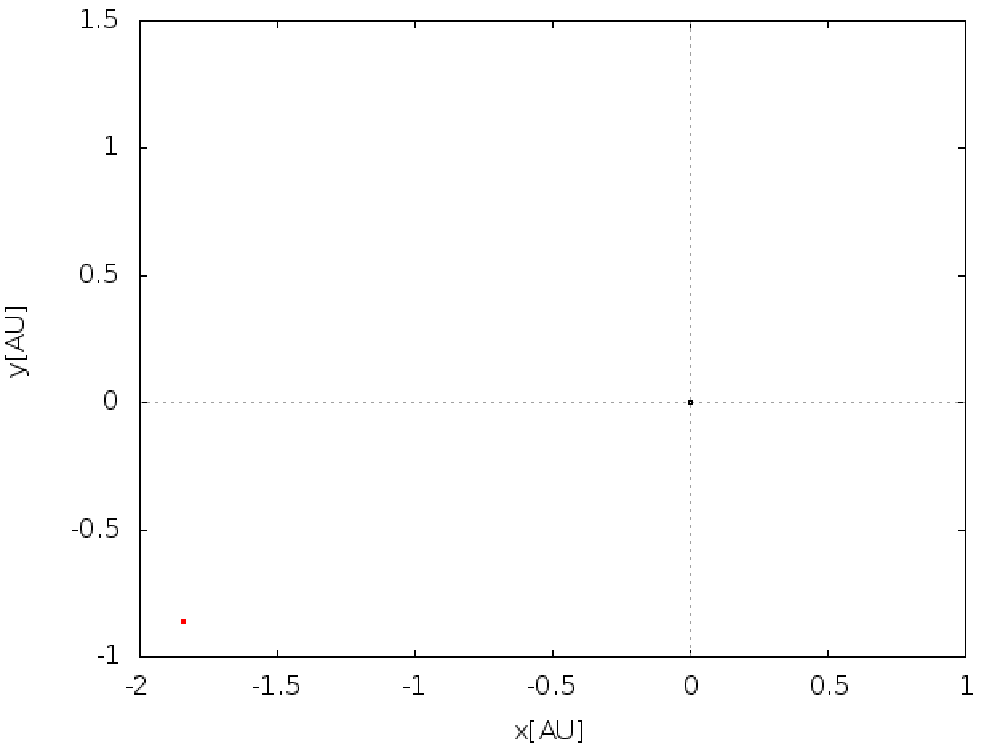
Spherical cloud (blue: M=10^-10 Mstar, green: 10^-8 Mstar

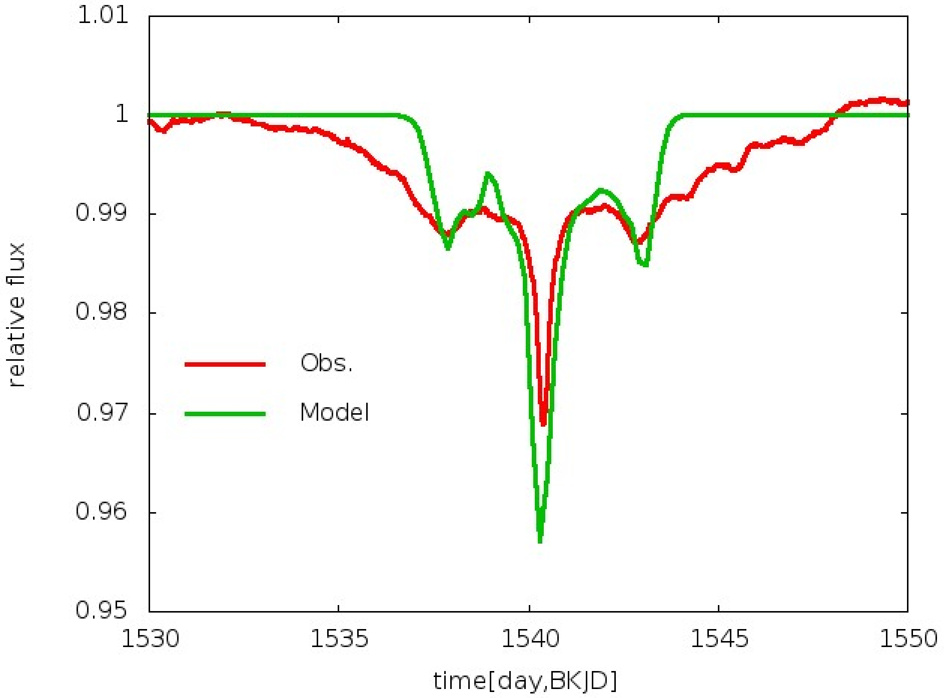


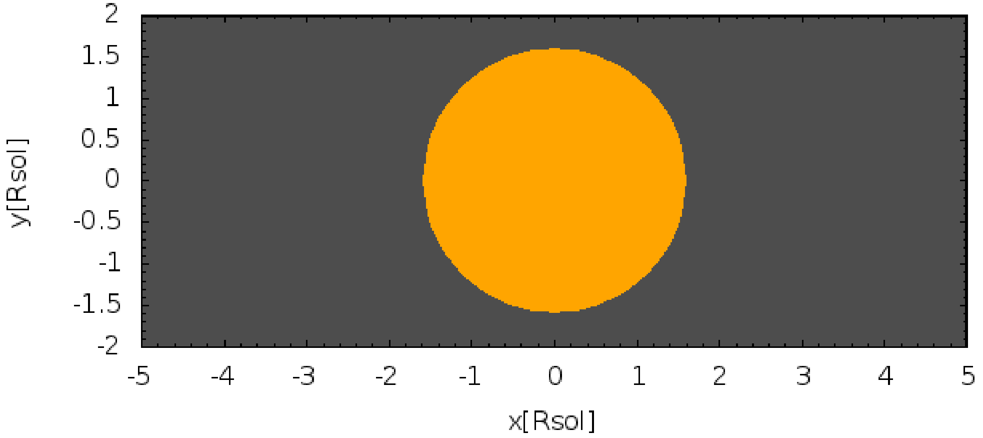


Massive bodies wrapped in the dust

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







Massive bodies wrapped in the dust

Pros:
-problems of the comet scenario are gone
-low number of free parameters

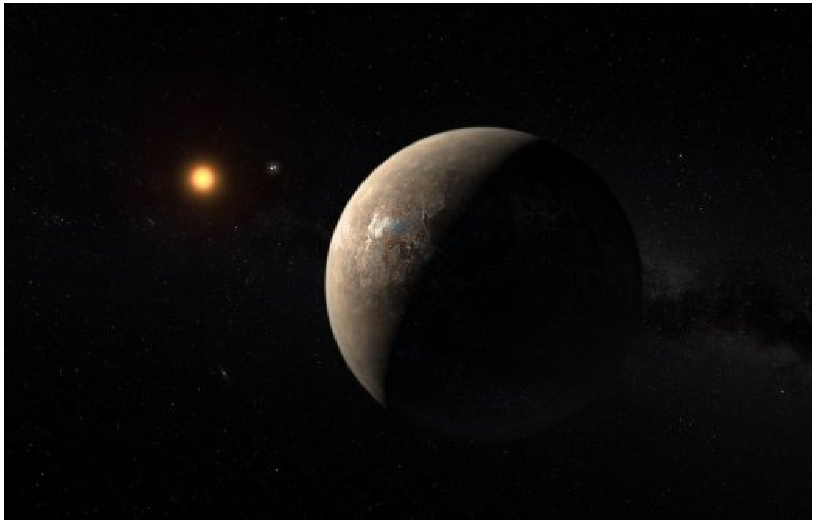
Cons:
-fits are not perfect (but surprisingly good given only a few free param)
-how to get a massive body on such eccentric orbit
-how to form a dust cloud around it

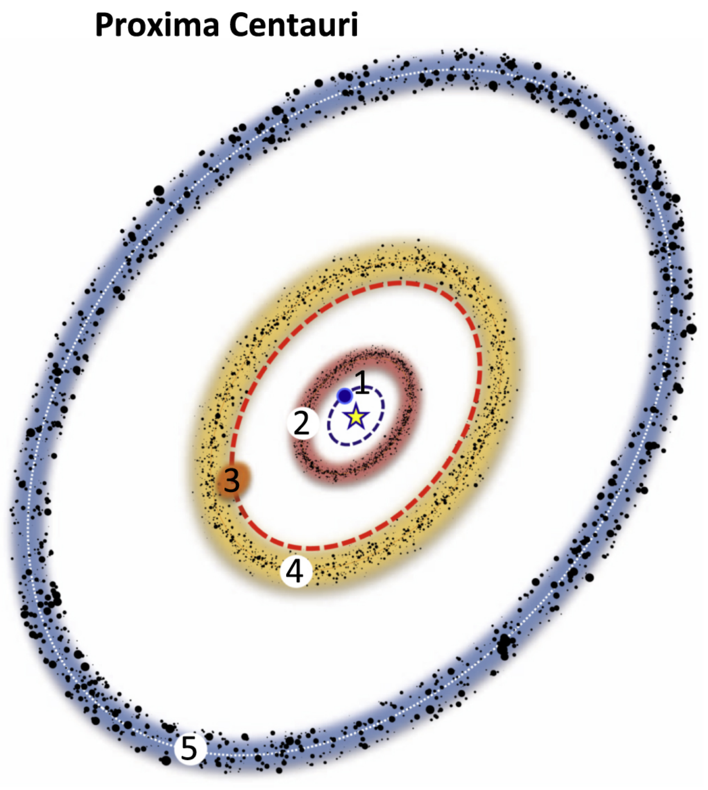
Granvik et al. 2016:
Super-catastrophic disruption of asteroids at small perihelion distances.

Proxima Centauri b

Discovered: Anglada-Escude et al. 2016,
method: rad. vel.
Star: active red dwarf, M
Distance: 1.3pc=4.2 ly, closest exoplanet
StarShot mission (1000x1cm/1g spacecrafts with a 1m sail, acceleration by laser, Yuri Milner, Stephen Hawking, Mark Zuckerberg)

Mass: > 1.2 Earth
Porb= 11 days
Rotation= synchronous
Habitable zone: yes
Rocky: yes





1. Proxima b planet r = 0.05 au
2. Warm dust? r ≈ 0.4 au
3. Unknown source? r = 1.6 au
4. Cold belt r ≈ 1-4 au
5. Outer belt? r = 30 au

Anglada et al. 2017
ALMA discovery of dust belts.