From disintegrating exoplanets to exoasteroids

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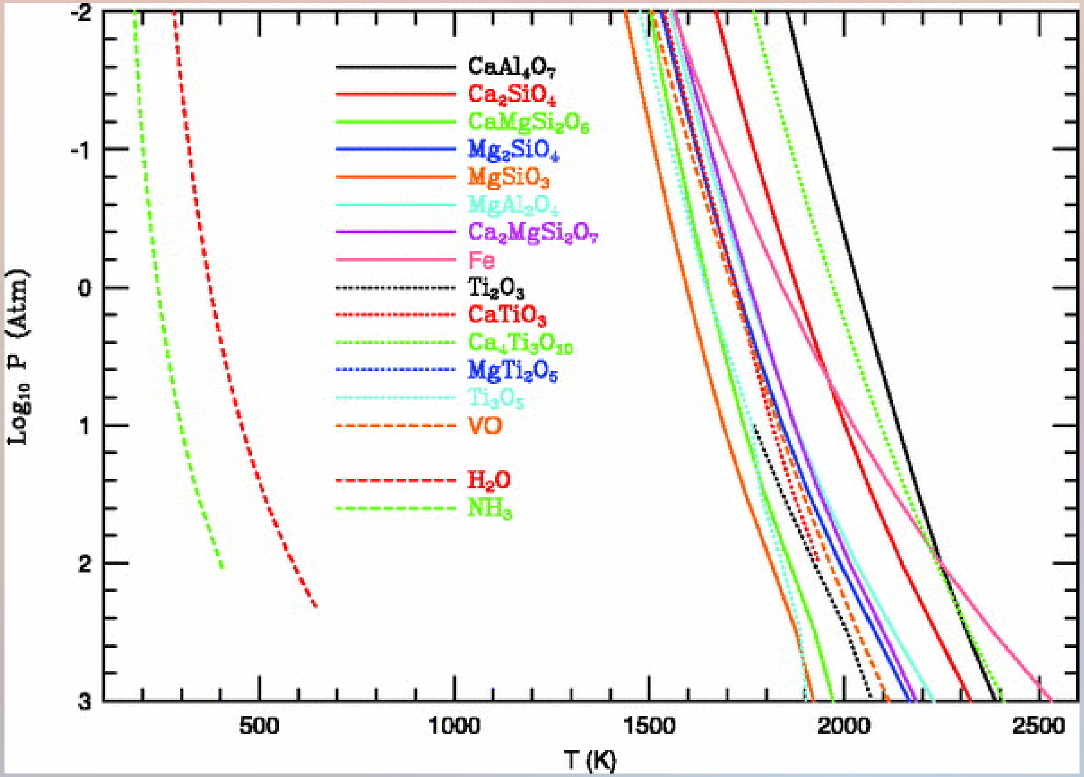
Dust & Clouds

What is dust, condensate, grain, cloud?

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

Most refractory species are composed of Ca, Al, Ti, Mg, Si, Fe: $CaAl_4O_7$-grossite, Al_2O_3-corundum, Silicates: olivine (Mg_2SiO_4-forsterite), pyroxene ($MgSiO_3$ enstatite), …

Then alkali metal chlorides, then H_2O and NH_3.



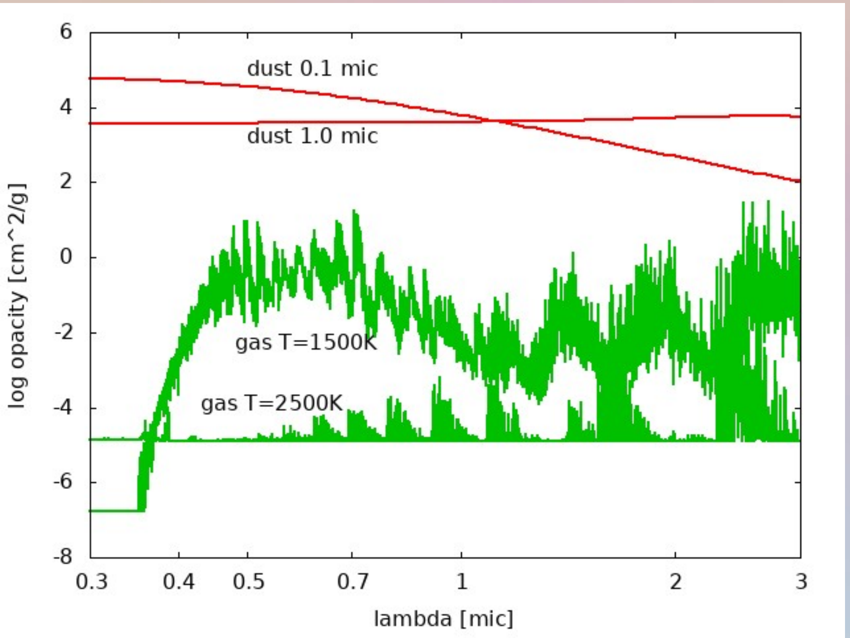
Optical properties of dust grains

Dust can absorb and scatter radiation. Extinction = absorption + scattering.
Interstellar dust typically causes reddening.
Dust affects the chemical composition. It removes the condensate from the gas phase.
Rain-out can transport dust into deeper layers creating chemical inhomogeneities.

Radiative acceleration (g-asymmetry parameter, β-radiative to grav. accel. ratio):

$$a_R = \frac{\pi R_{star}^2}{Mcr^2} \int [C_a + (1-g) C_s] B_\nu (T_{star}) d\nu \qquad \beta = \frac{a_R}{a_G}$$

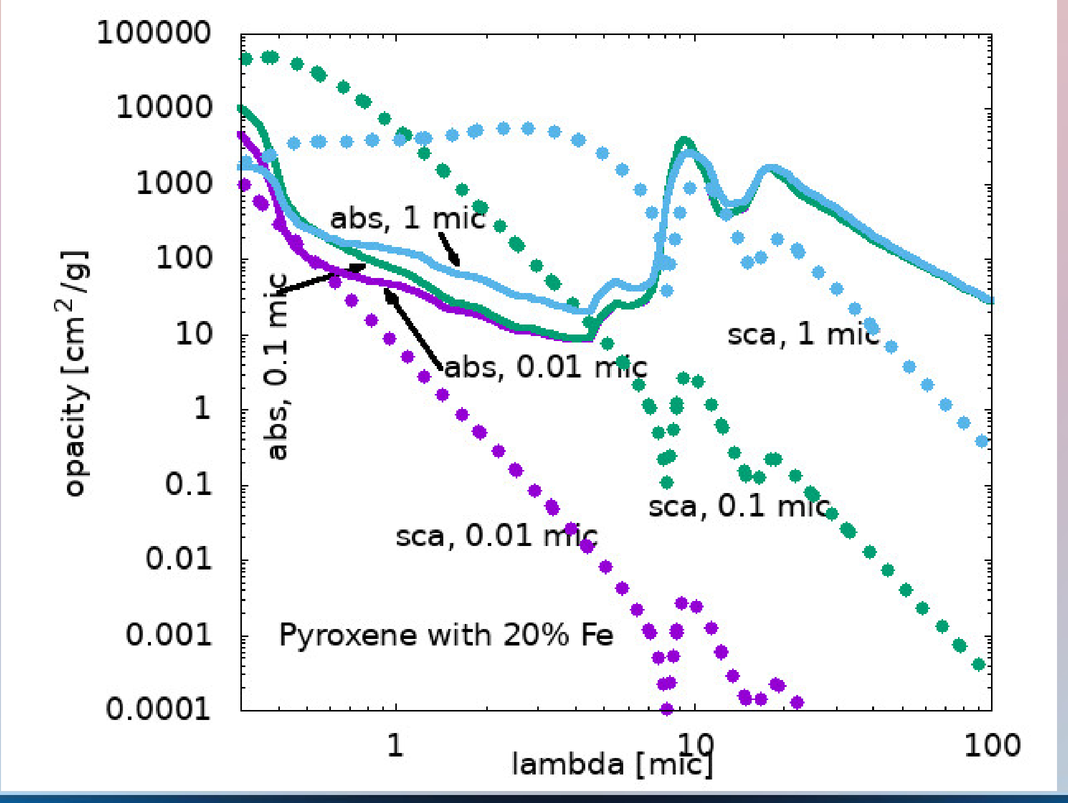
Dust is much more effective absorber/scatterer than gas.
Picture shows opacity of forsterite per gram of dust for two particle sizes and opacity of gas at two different temperatures (Budaj et al. 2020).
It can be demonstrated by everyday experience: visibility drops from 100km to 10m following water condensation.



Tables of dust opacities, albedos, equilibrium temperatures, radiative accelerations, and phase functions for extrasolar planets

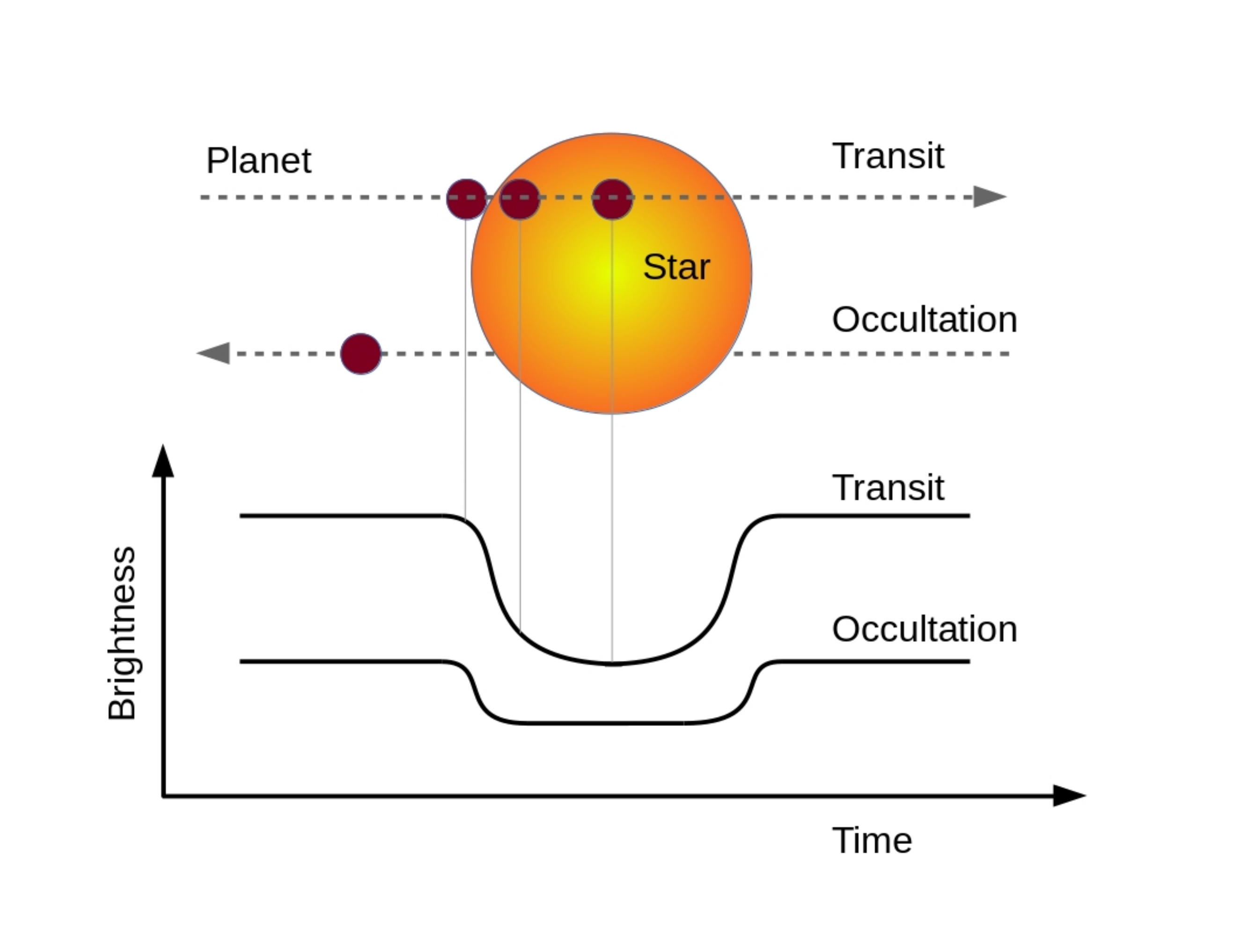
Budaj, Kocifaj, Salmeron, Hubeny 2015

Particle size 0.01-100 mic, lambda 0.2-500 mic., iron , carbon, silicates (pyroxenes, olivines), water (ice , liquid), ammonia



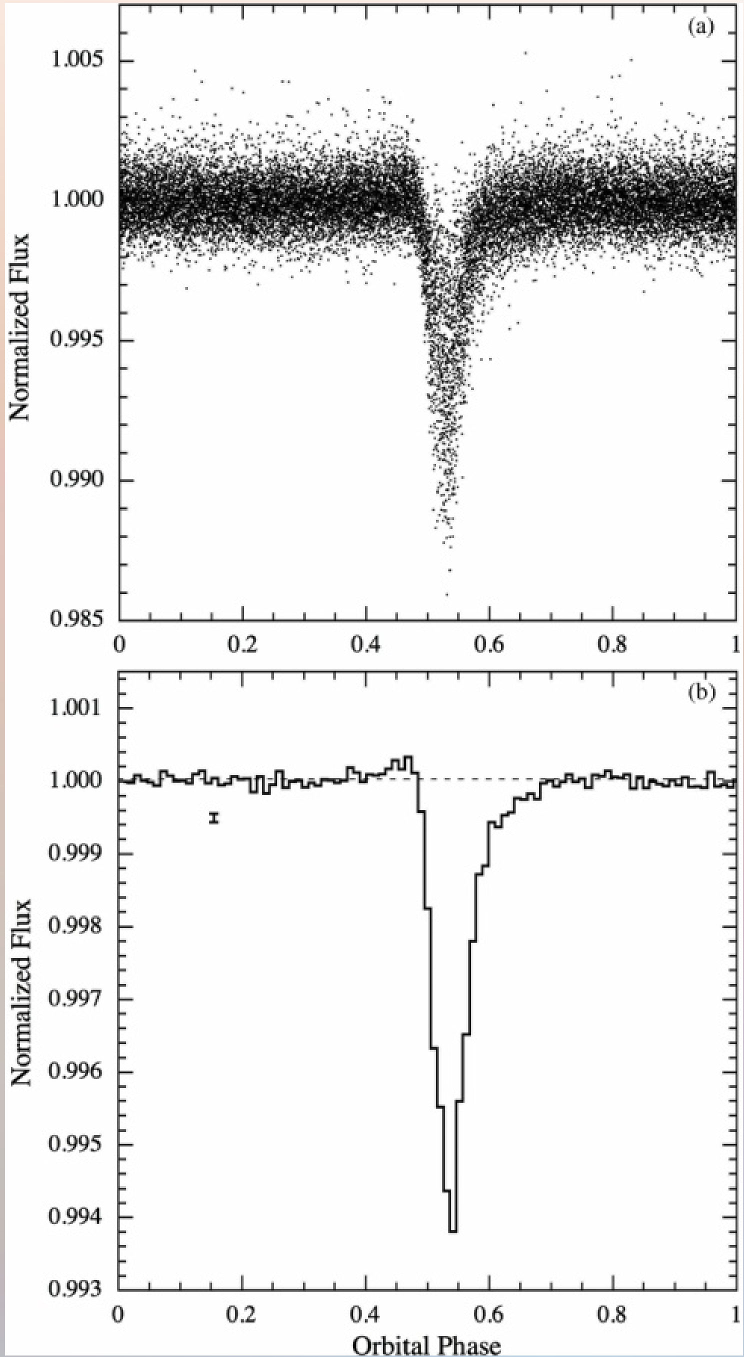
Transit of the planet

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

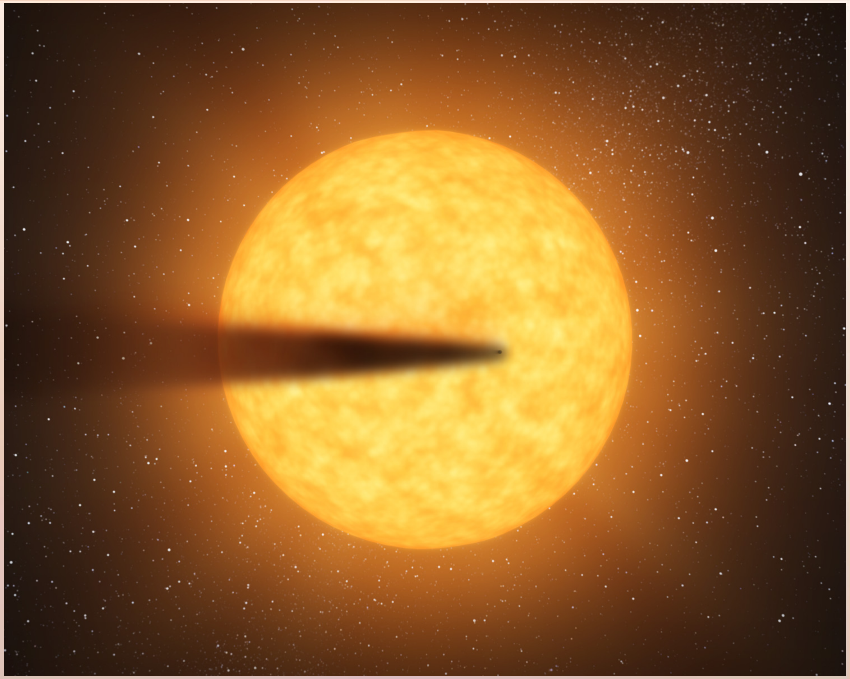


Kepler 1520b: Exo-planet or exo-comet?

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



Kepler 1520b interpretation



Rappaport et al. (2012)

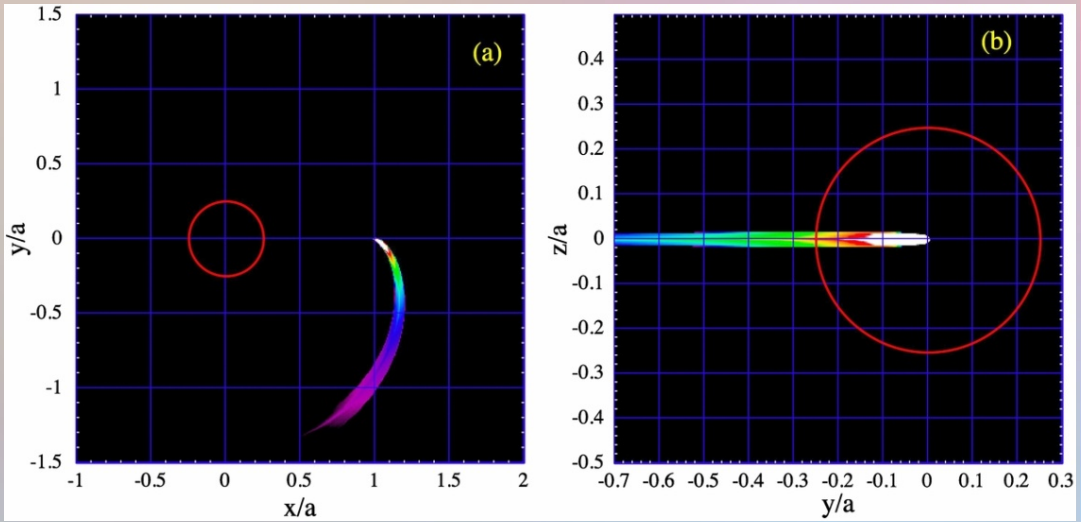
Mercury size planet

Close to the star, surface melts, evaporates, escapes from the planet

Comet like tail made of dust

Planet has lost most of its mass

Opportunity to study planet interior



Kepler 1520b

Budaj 2013

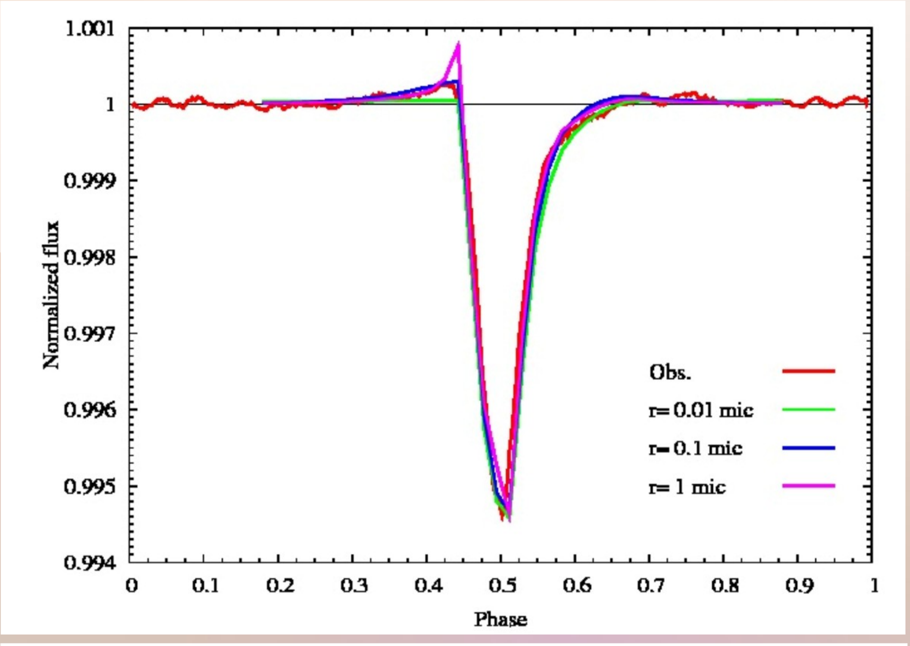
Code: Shellspec

Physics

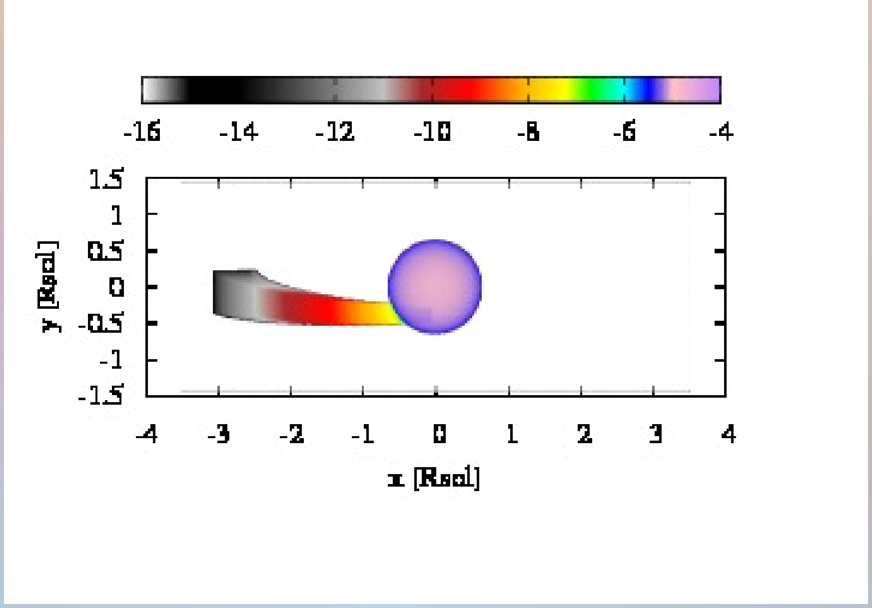
·Radiative transfer along the line of sight
·Absorption (Mie scattering + t. absorption)
·Emission (Mie scattering + thermal)
·Dust opacities + phase functions
·Forsterite, Estatite, Pyroxene with 20% Fe, iron

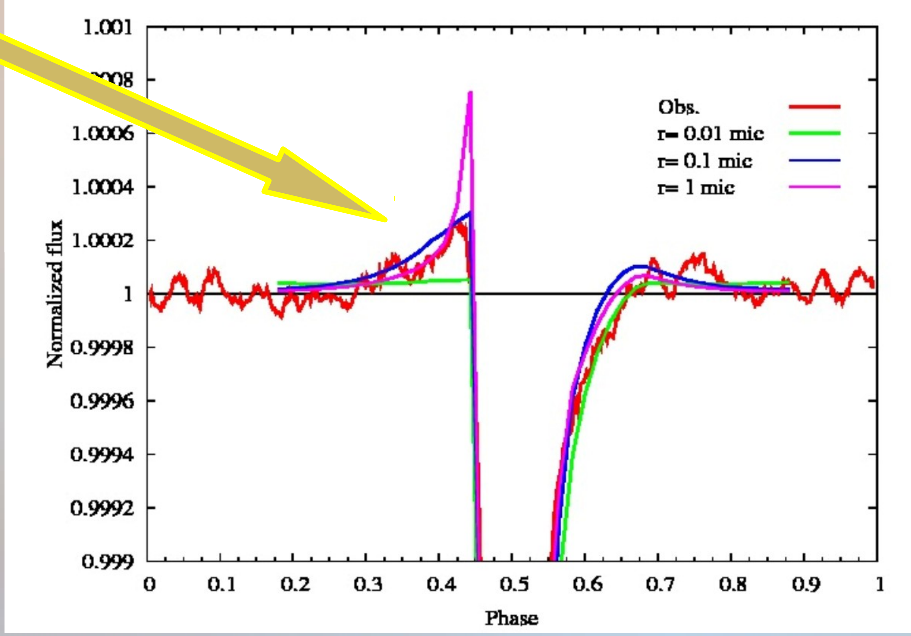
Geometry

·Arc 60 deg, increasing cross-section
·Density decreasing along the arc

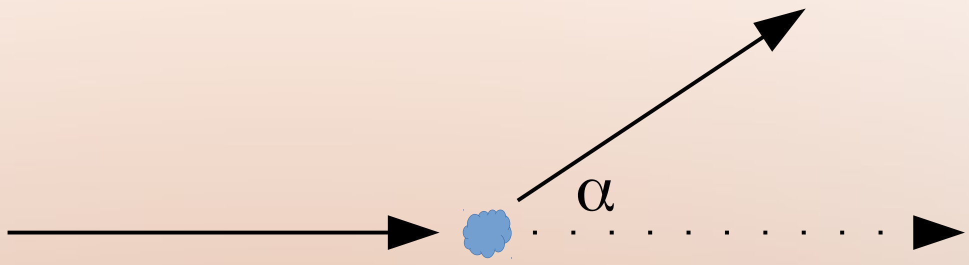


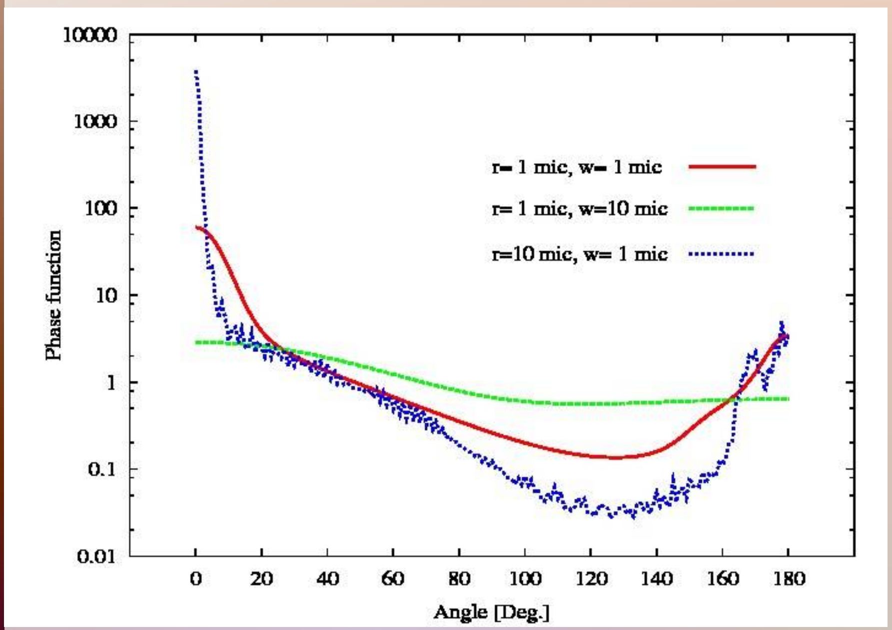
Pre-transit brightening





Phase function

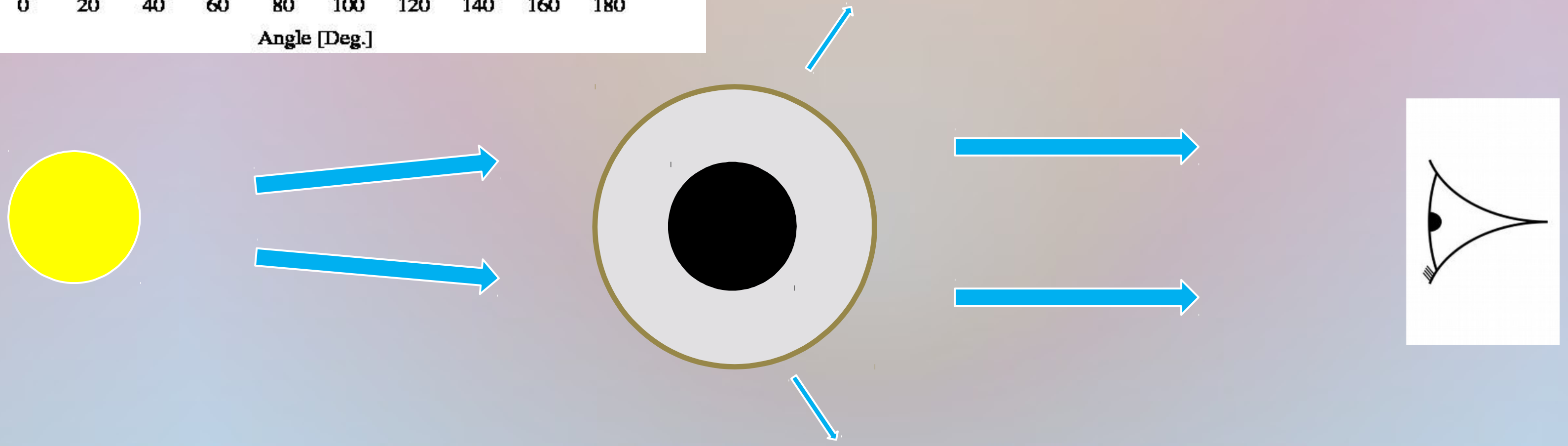




Dust does not scatter light isotropically.

Phase function describes an angular distribution of the scattered light as a function of phase angle (deflection from the original direction).

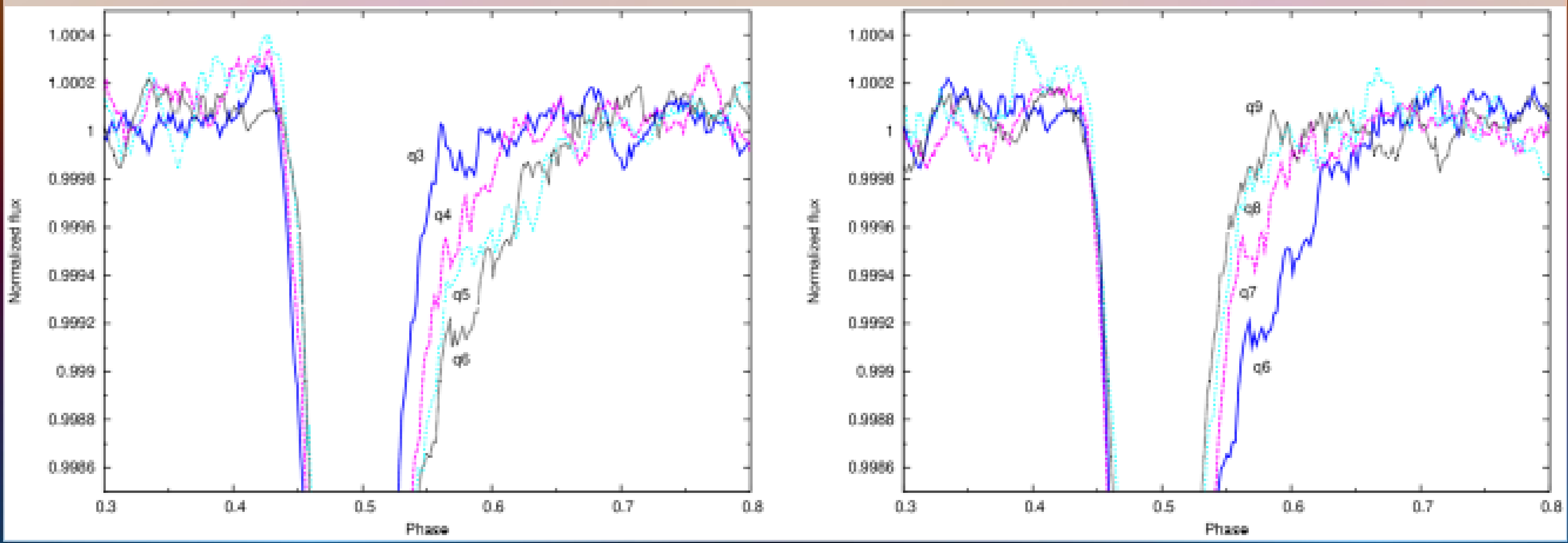
Strong forward scattering is causing the pre-transit brightening.



Kepler 1520b: Tail evolution

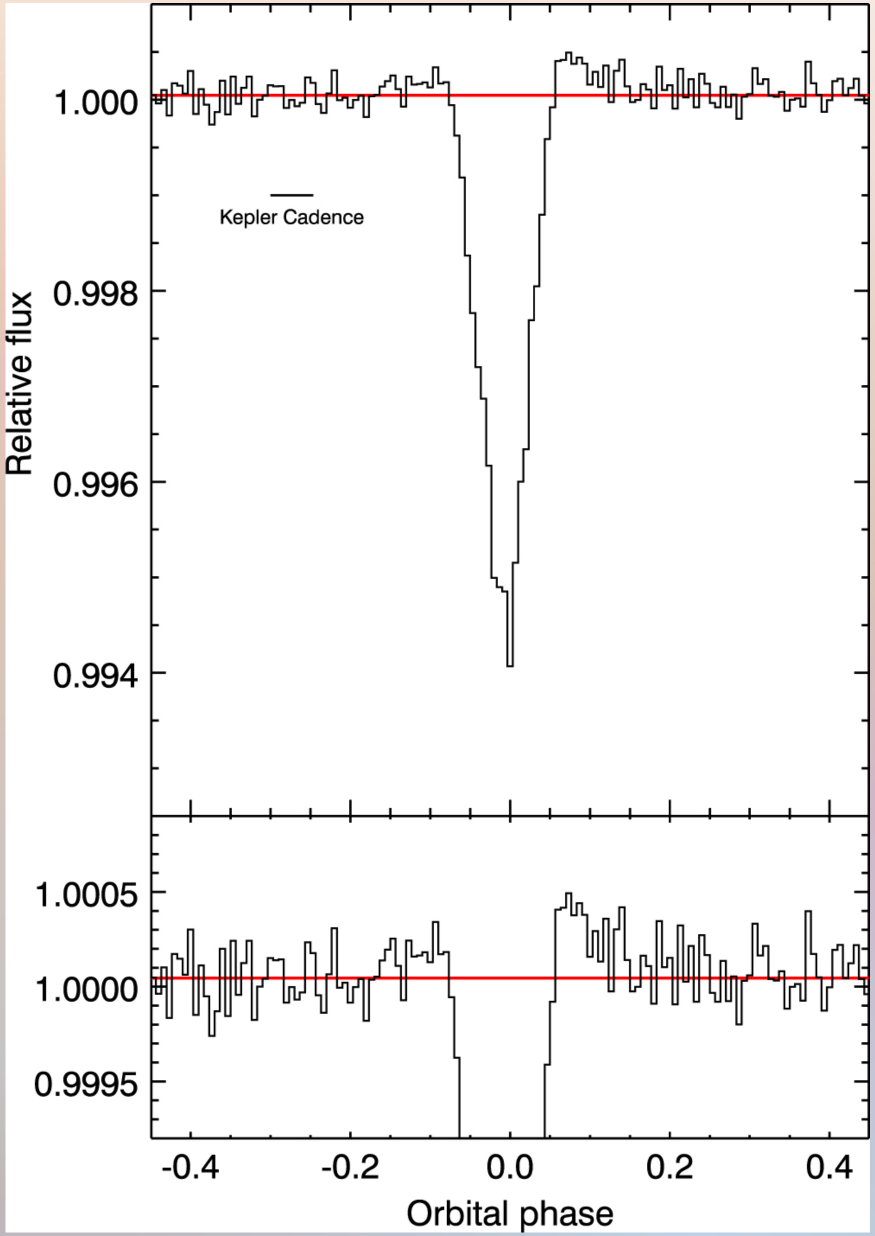
- Quasi-periodic strengthenning – weakenning of the tail, 1.3 yr
- Stellar magnetic or wind activity, cycles, CMEs?
- Analogy to comet-tail disconnection?
- Additional planet?

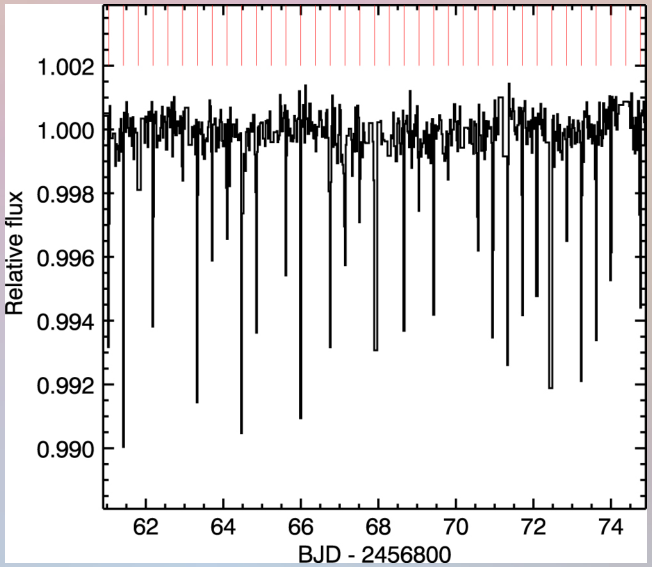
Budaj, 2013, A&A 557, A72



Exo-planet: K2-22b

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



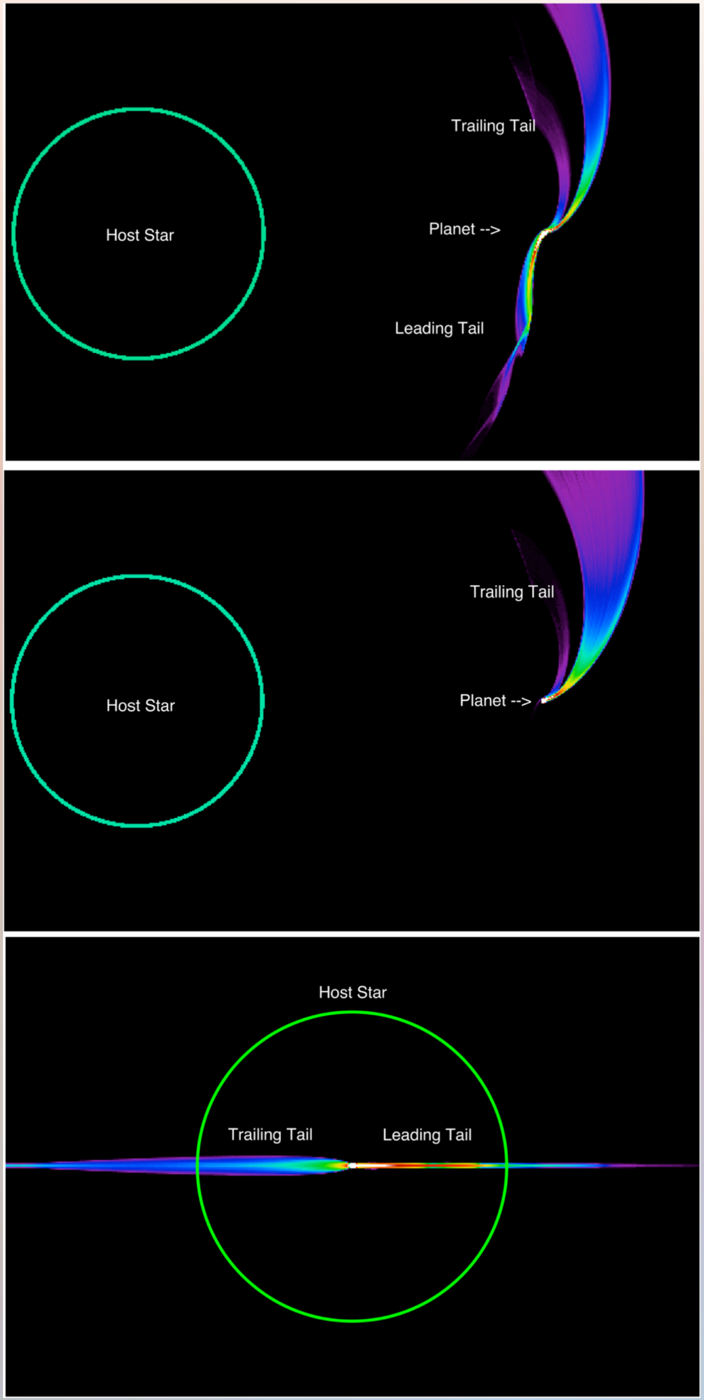


Exo-planet: K2-22b

Sanchis-Ojeda et al. 2015

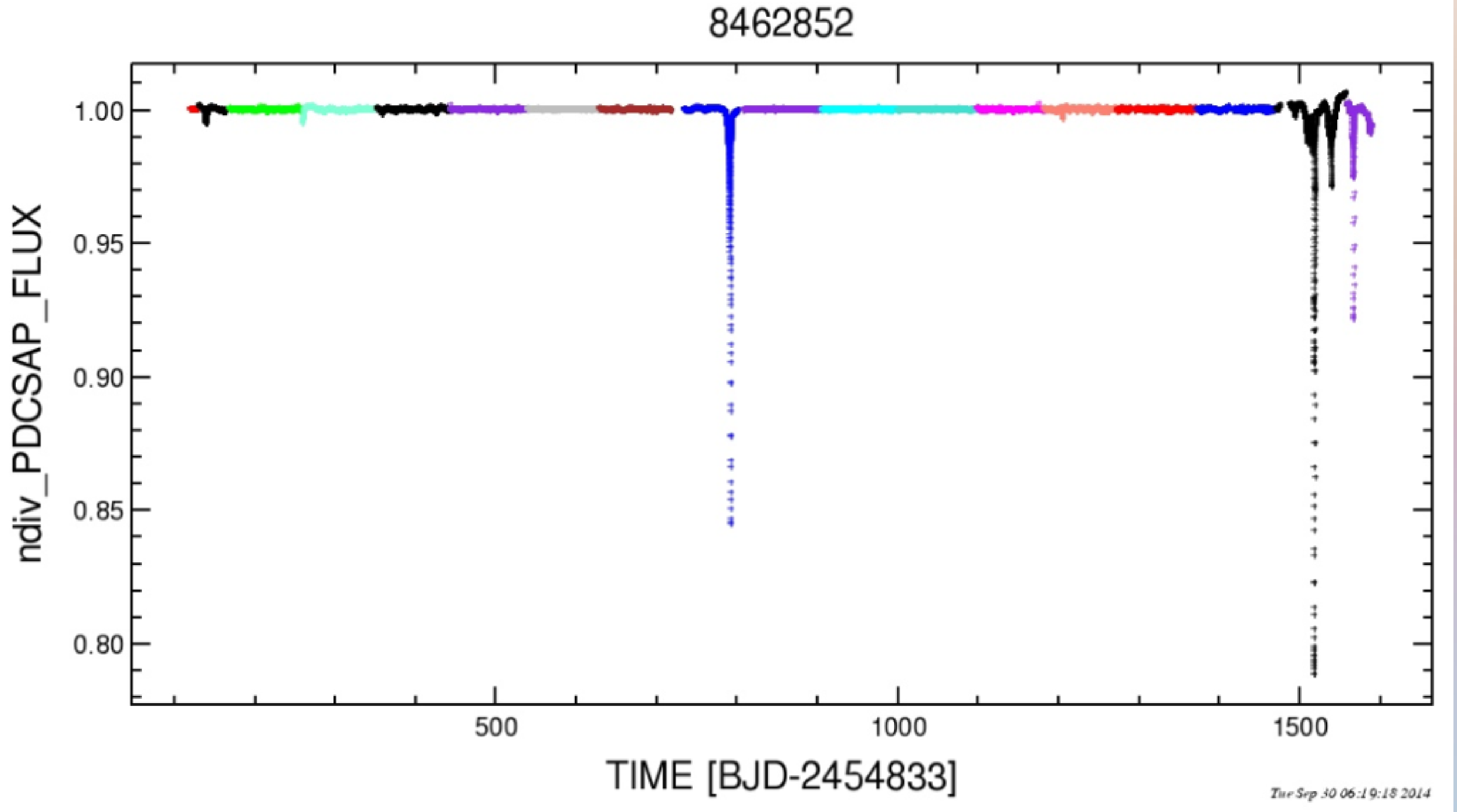
M0 => Low luminosity star => radiative pressure is weak => gravity wins => leading tail

Middle panel is for artificially enhancing beta 4 times.



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



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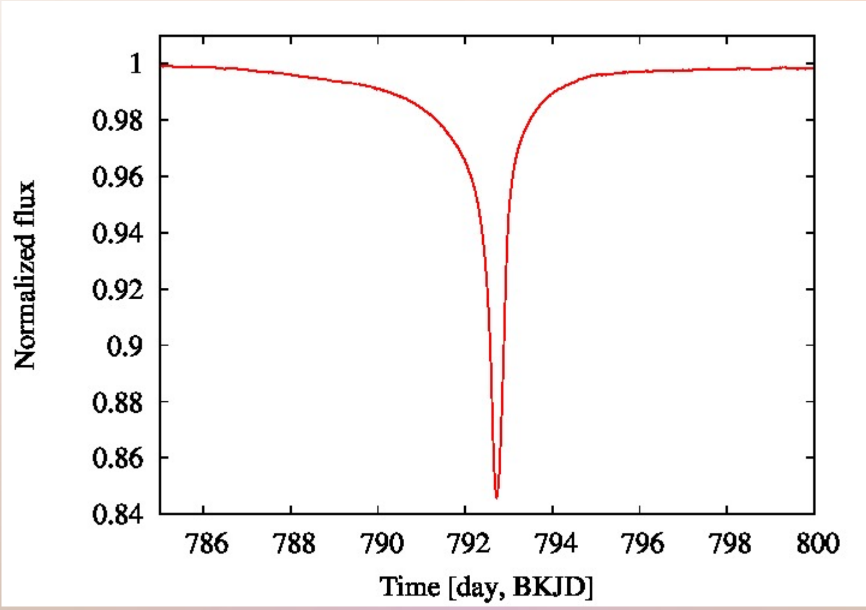
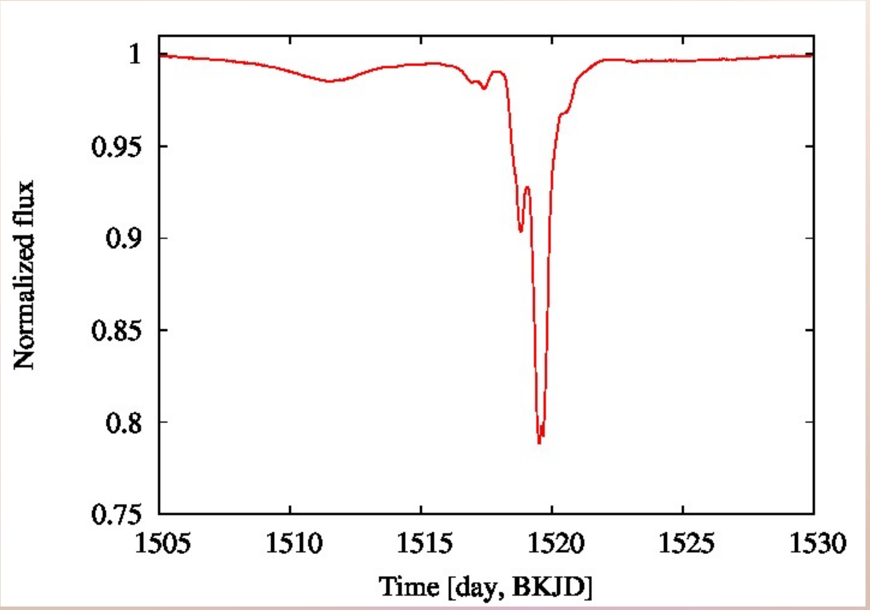
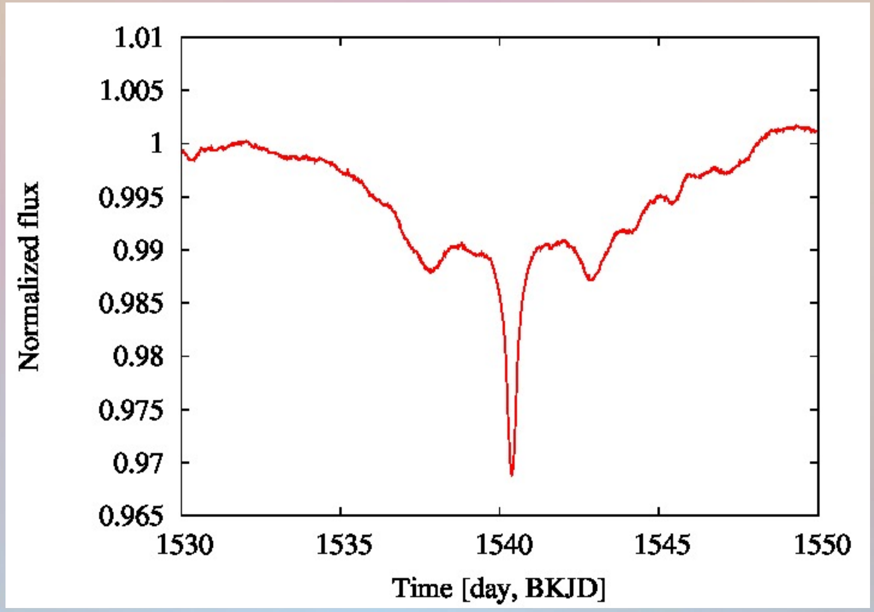
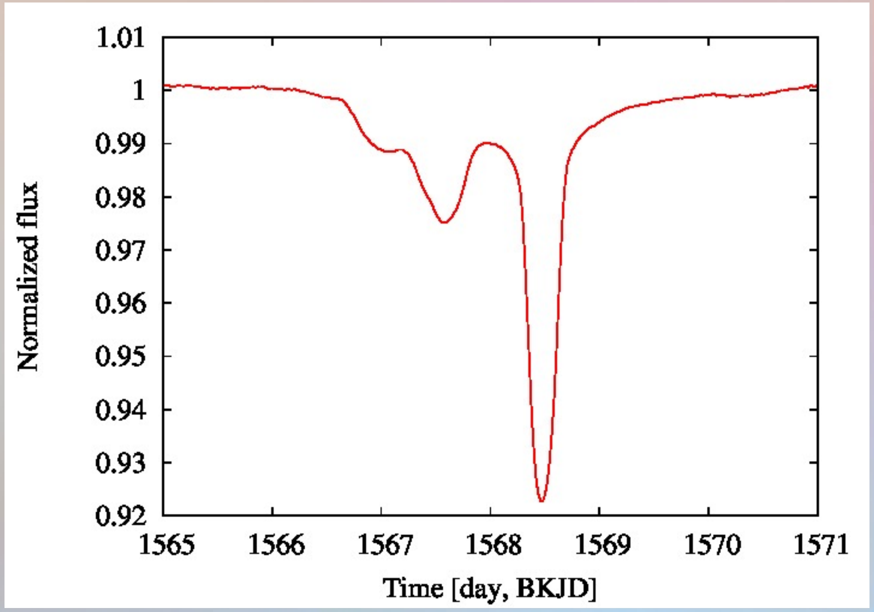
Shapes of four main events





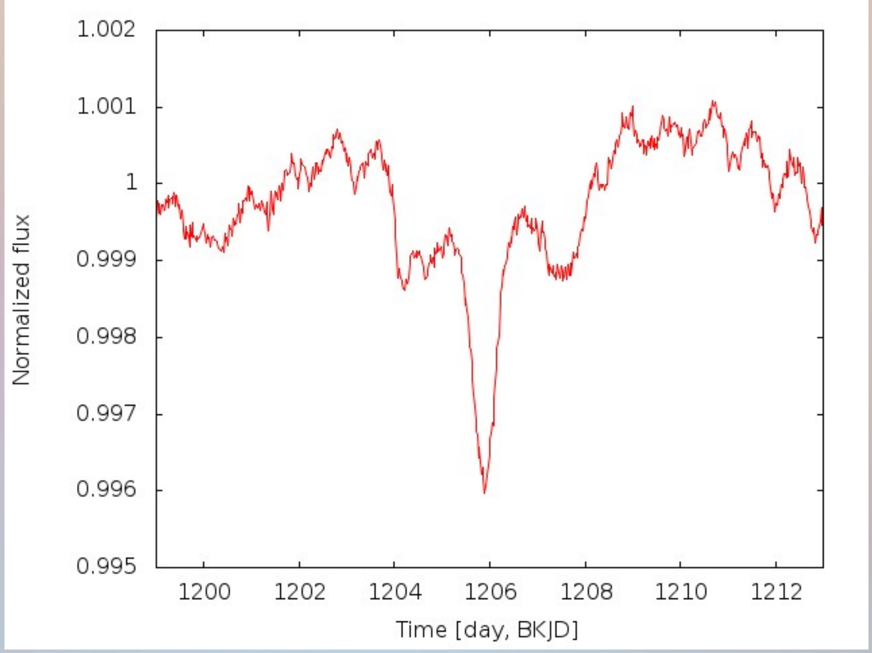




IR,sub-mm,mm,GAIA

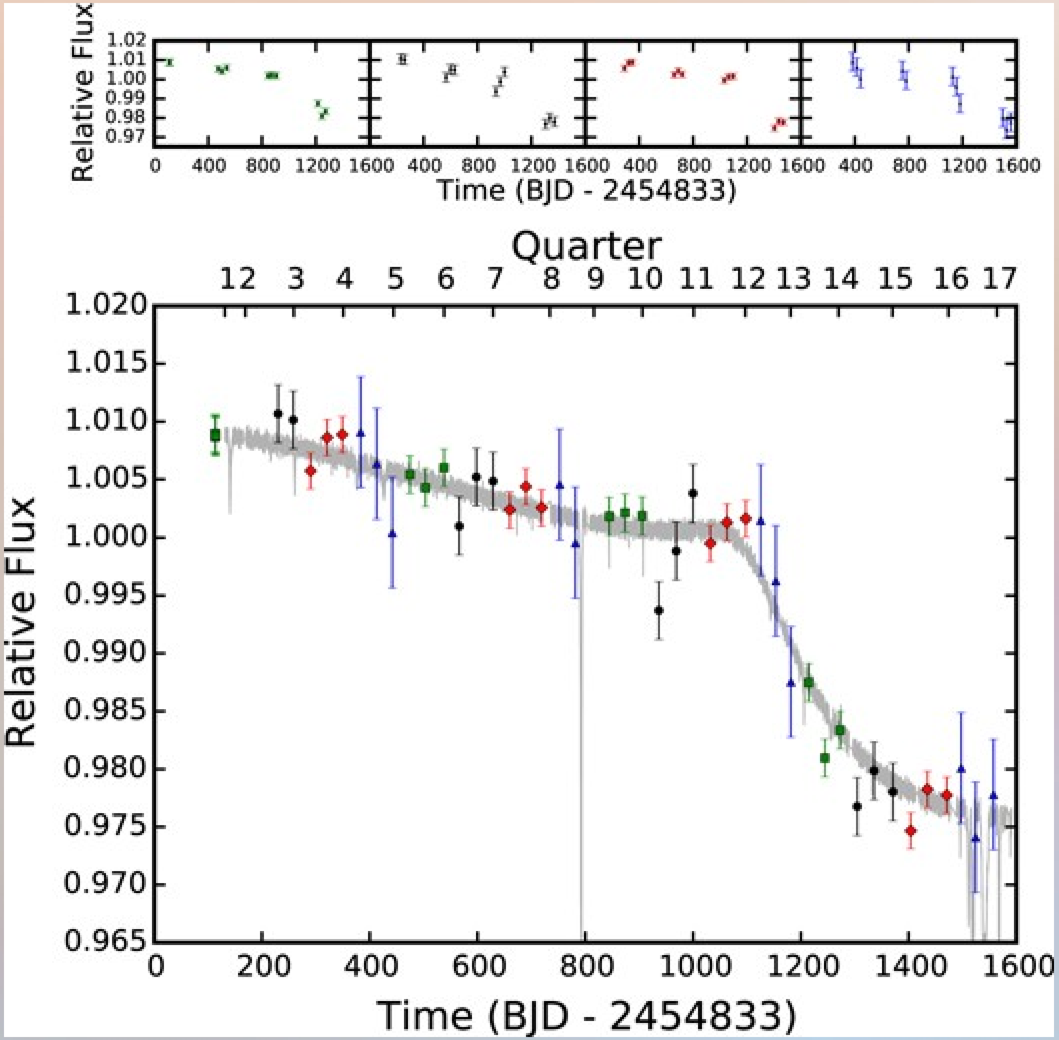
- Boyajian et al.2016, Marengo et al. 2016
- Lisse et al. 2015, Thompson et al. 2016
- Hippke & Angerhausen 2017 (GAIA, 390pc)
- Nondetection, not young object
- Dust <7.7 M_Earth within 200au
- Dust in occultation < 10^-3 M_Earth

Another event



Long term trend

Montet & Simon (2016)



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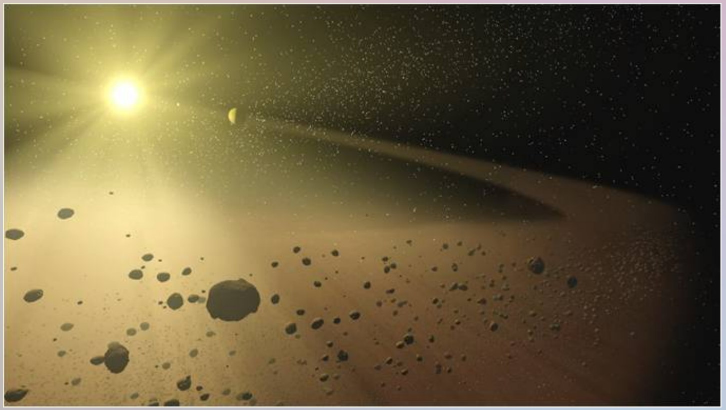
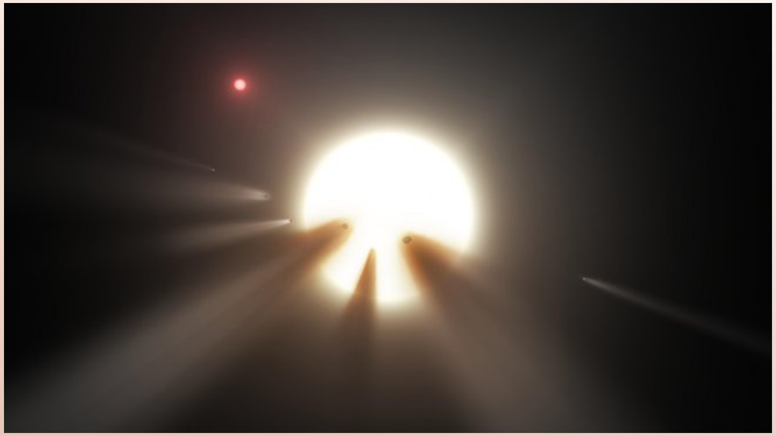
Plenty of ideas:

-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
...



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

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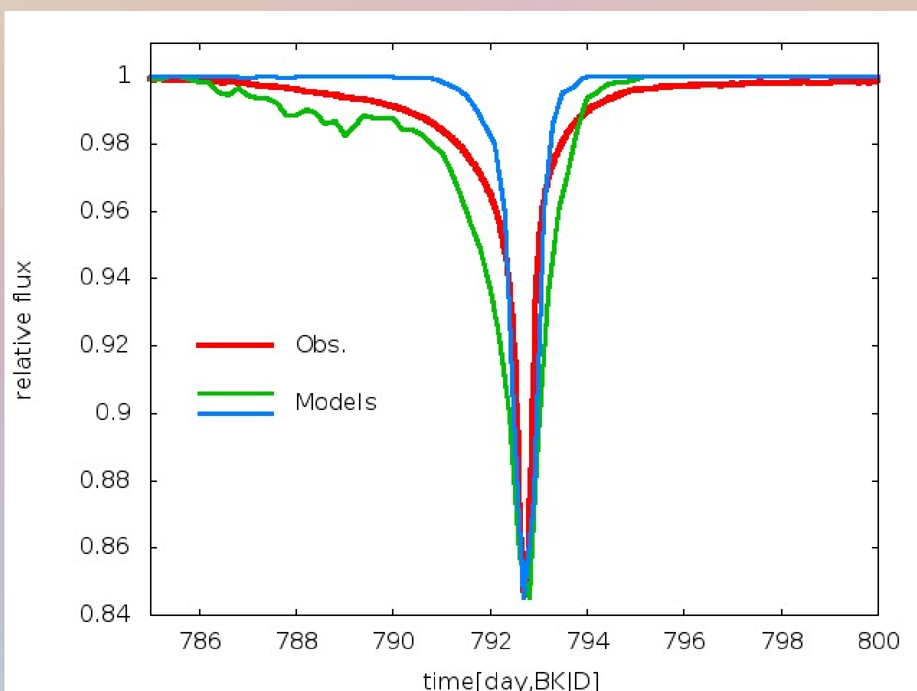
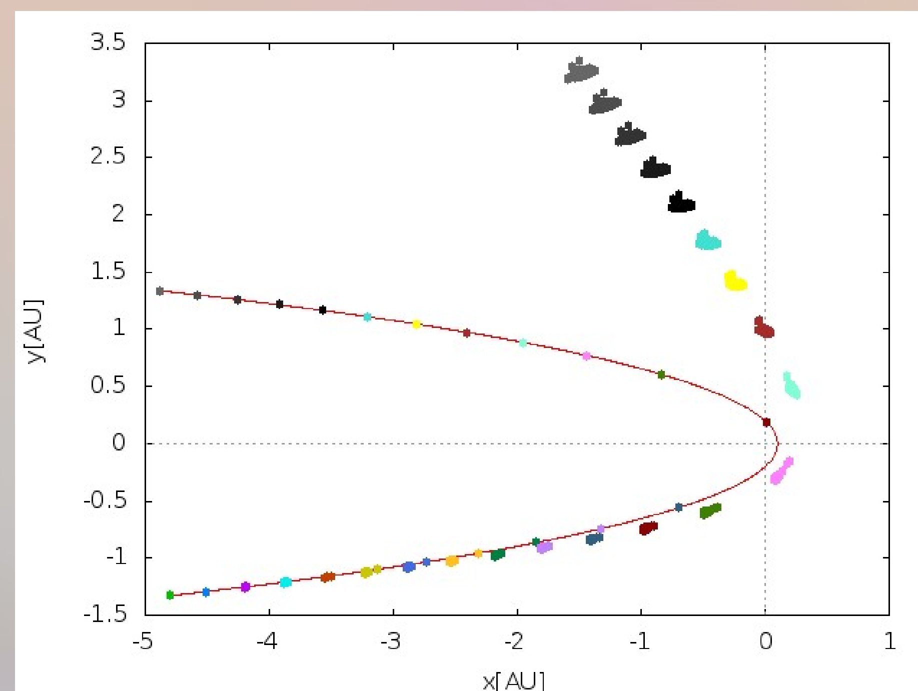
Massive bodies wrapped in the dust

- 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





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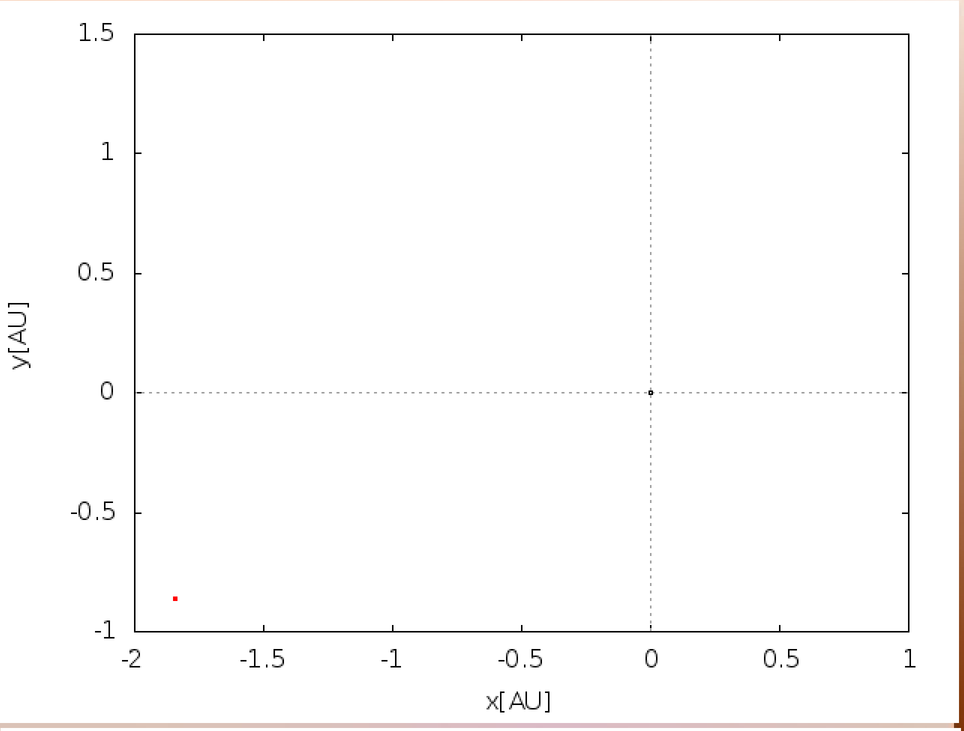
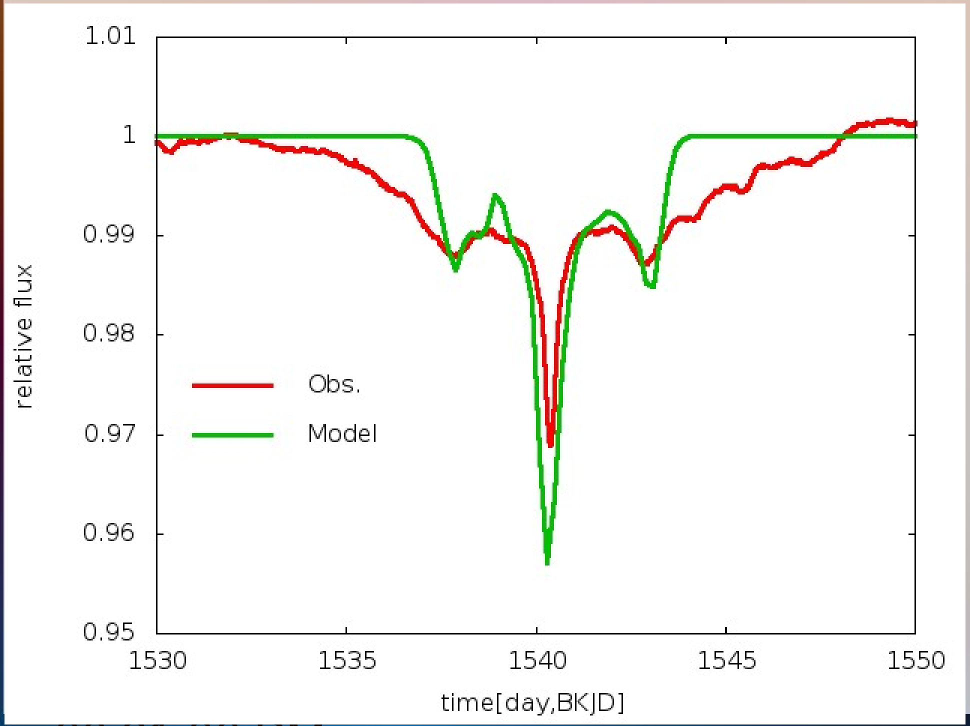
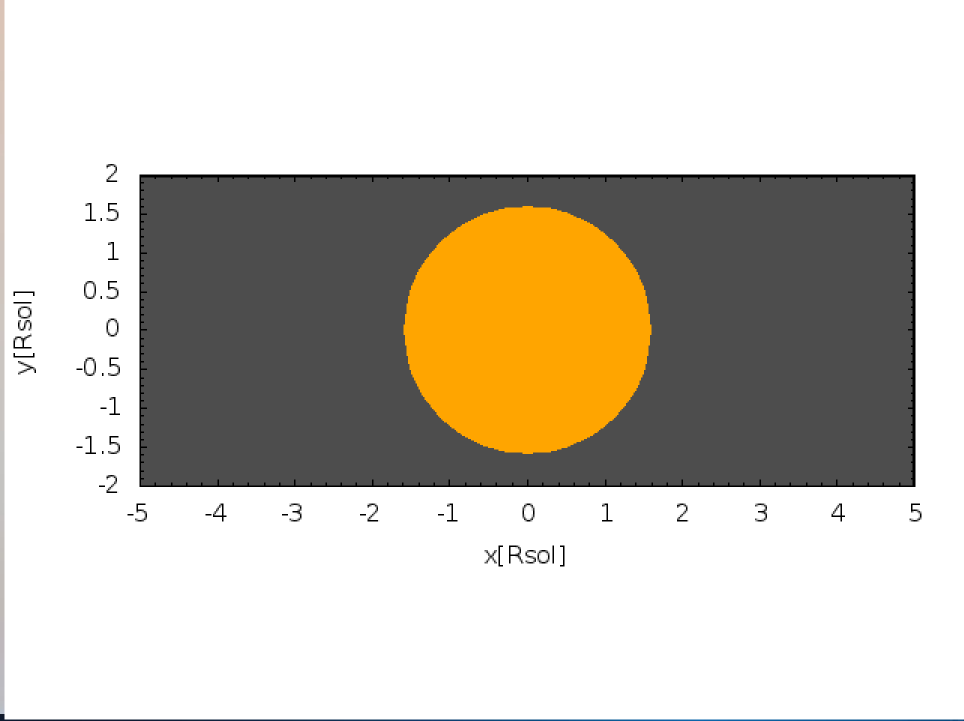
Massive bodies wrapped in the dust

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







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Massive bodies wrapped in the dust

Pros:
-problems of the comet scenario are gone
-low number of free parameters (fits are not perfect but quite good)
-can produce small or comet-like debris

Cons and further questions:
-how to get a massive body on such eccentric orbit
-how to get 4 or more massive bodies on identical orbit
-how to form an initial dust cloud around it

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

Intro into DZ WDs

WD classification:
DA-hydrogen lines
DB-helium lines

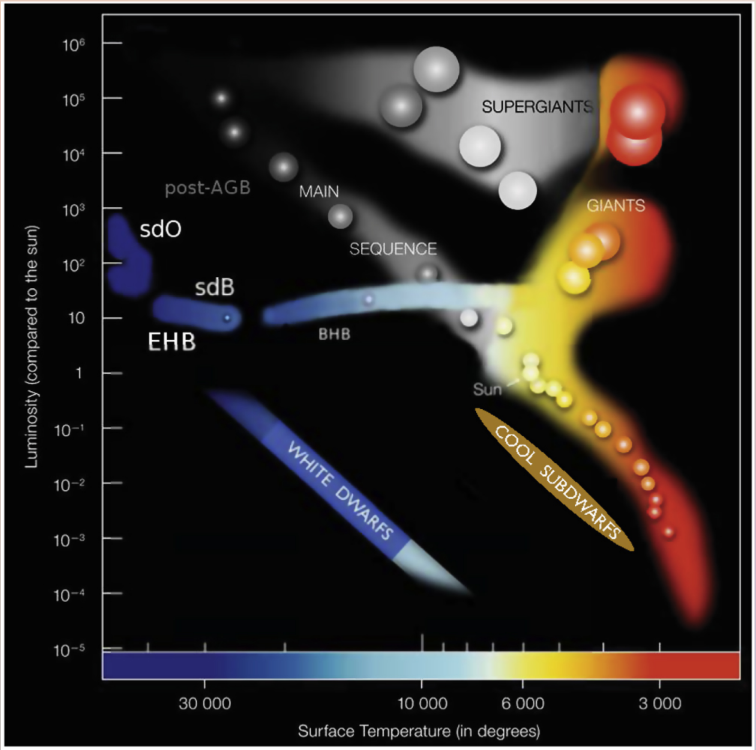
-1/4-1/2 of WDs show lines of heavy elements and are called DZ type WDs

-some WDs have IR excess (dust)

-problem:
WD are very small 1/100 Rsun, gravity is very high 10^4 time Gsun =>
Heavy elements should sink quickly

-WD enable detection of small objects in transit

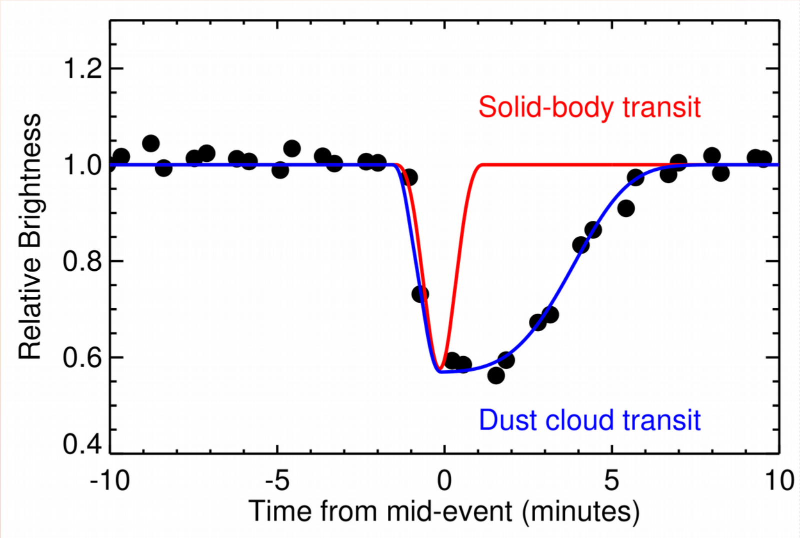
$$\Delta F \approx \left(\frac{R_p}{R_s}\right)^2$$



Intro into WD1145+017

-DBZ type, 1st exoasteroids detection

-Vanderburg et al. 2015 from K2 data, transit-like, variable, more than 40% deep, asymmetric signal, P=4.5h, dust tail transits (not solid body)

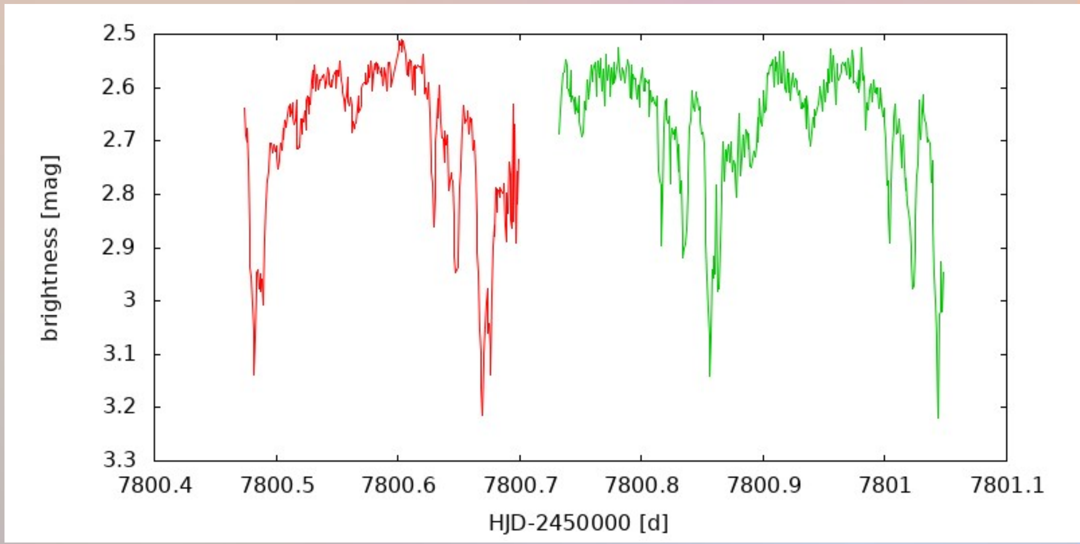


Vanderburg et al. 2015

-light curve evolution, disintegration, many (>6) bodies with similar periods

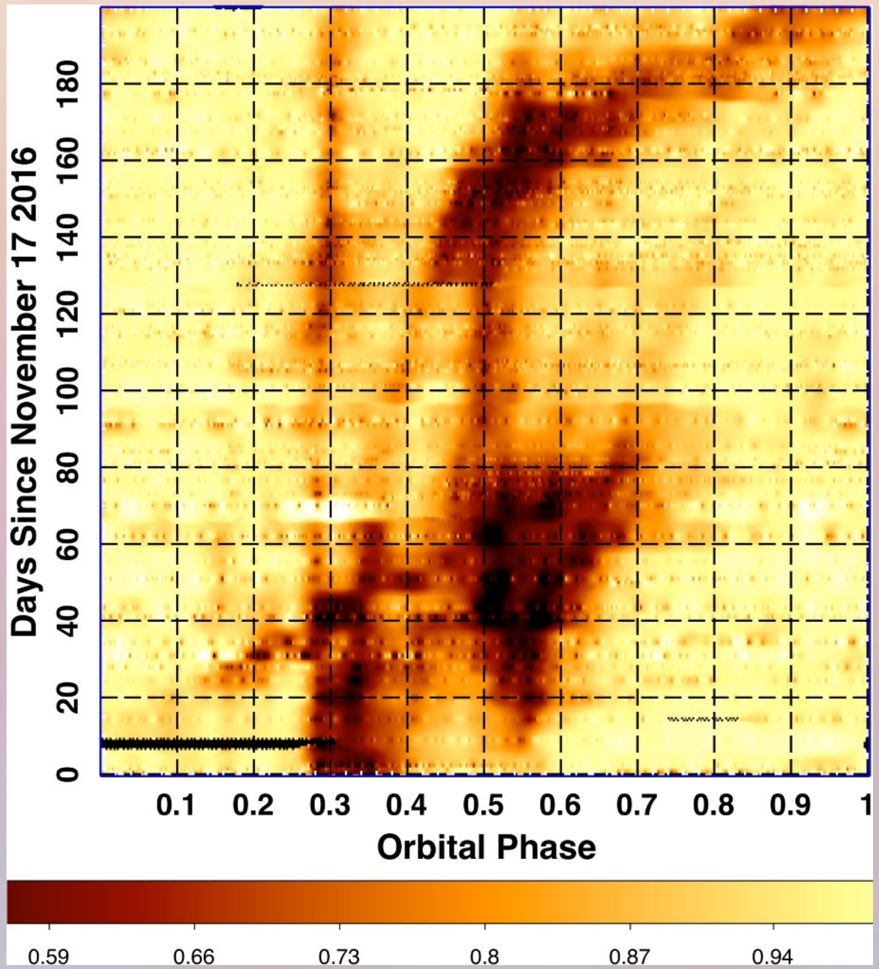
-shallow UV transits (Xu et al.2019)
-IR excess (dust)

-broad circumstellar lines of metals (gas disk)



Maliuk et al. in preparation

Exo-asteroids: WD 1145+017



Rappaport et al. 2018

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Observations

-17 mag, north hemisphere

Archival data from Xu et al. 2016,2019,
Cauley et al. 2018:

-Keck/HIRES, R=40000, optical

-VLT/X-SHOOTER, R=7000, optical

-HST, R=20000, UV

-transit depth measurements from Xu et al. (2019)
(HST, Keck, VLT, Spitzer / 1300, 4800, 5500Ang., 4.5mic)

-GAIA DR3 parallax → 145.5+-1.9 pc

Atmosphere models

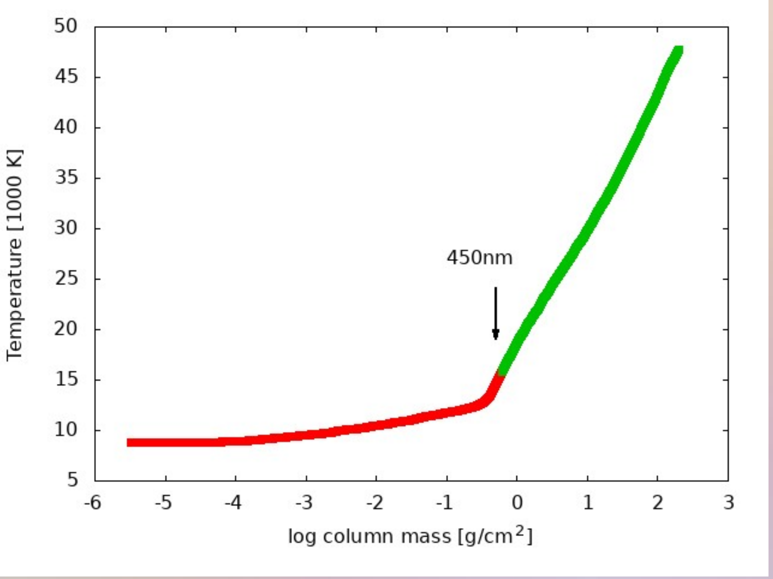
TLUSTY 209 (Hubeny et al. 2021):
-LTE
-Restricted NLTE model
(HI-II, HeI-III, CI-III, OI-III, MgII-III, AlII-IV, SiII-IV, FeI-IV)

-first DB/DZ white dwarf analyzed with TLUSTY

-new physics: HeI level dissolution

-Teff=15000K, logg=8.0 [cgs], vt=3km/s, vrot=0km/s

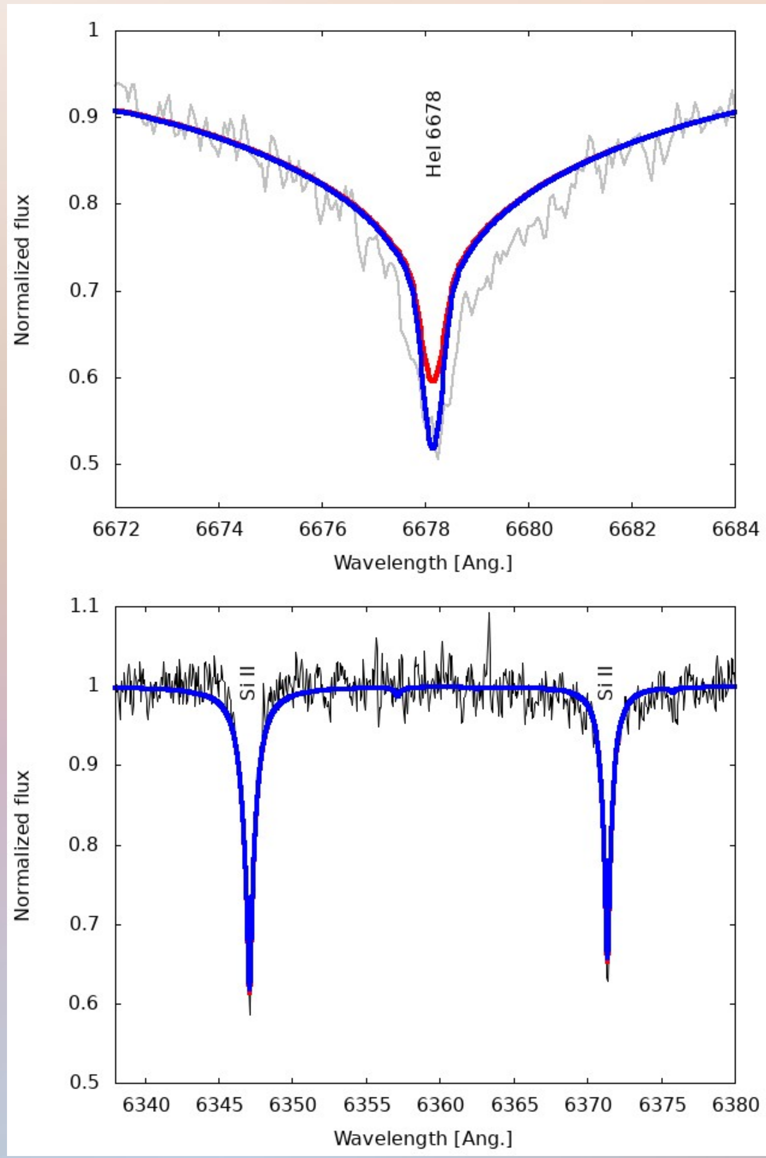
SYNSPEC54 (Hubeny et al. 2021)
-chemical composition derived from optical+UV spectra

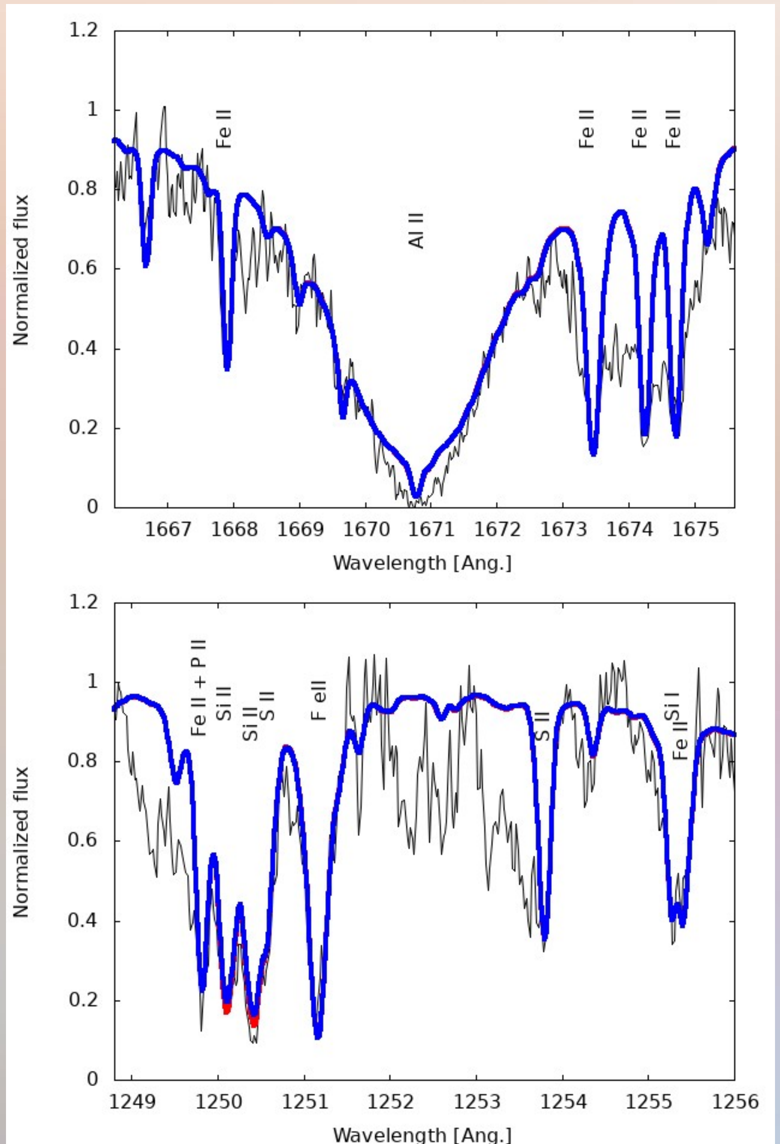


green=conv. zone (Budaj, Maliuk, Hubeny 2022)

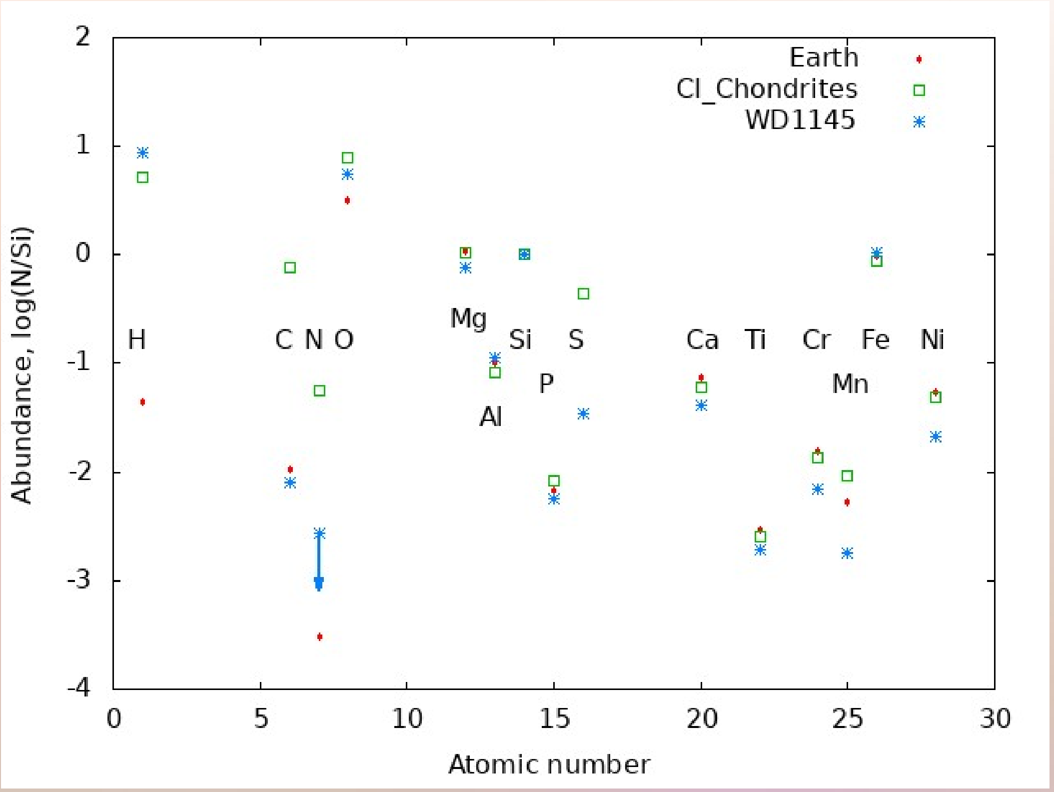
Spectra

Plenty of metal lines in UV and optical region.
LTE=red, NLTE=blue, obs.=grey





Chemical composition



Budaj et al. 2022

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

How is it possible?

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

-plenty of indirect evidence to support it but...

-WD1145 is the first direct proof of the hypothesis. We see it all happening in front of our eyes: asteroid, its disintegration, dust clouds, gas disk, and now also the chemical composition of the atmosphere!

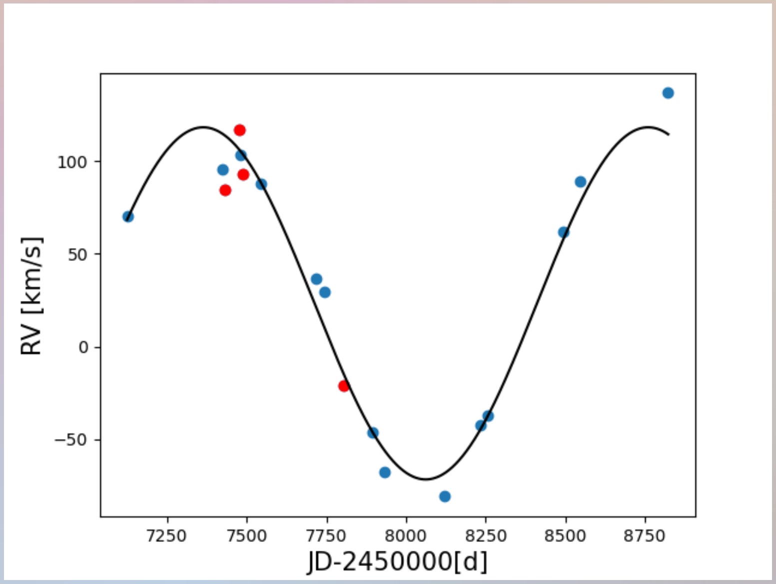
Metals are mixed in conv. zone

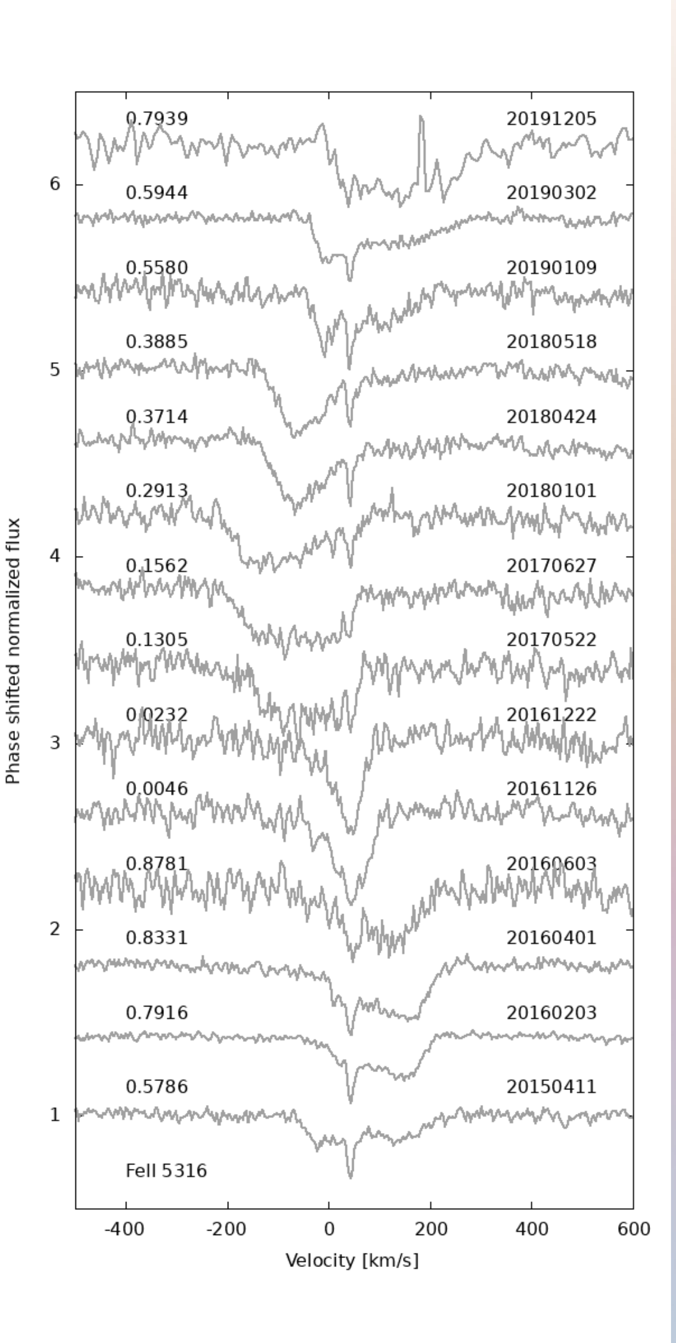
Circumstellar lines and gas disk

sharp component: star, gravit. redshift 43km/s

broad component: circumstellar material, moving

RV: Period=3.83+-0.12 yr, Amplitude=94.9+-5.0 km/s
FeII 5316, Keck=blue, VLT=red





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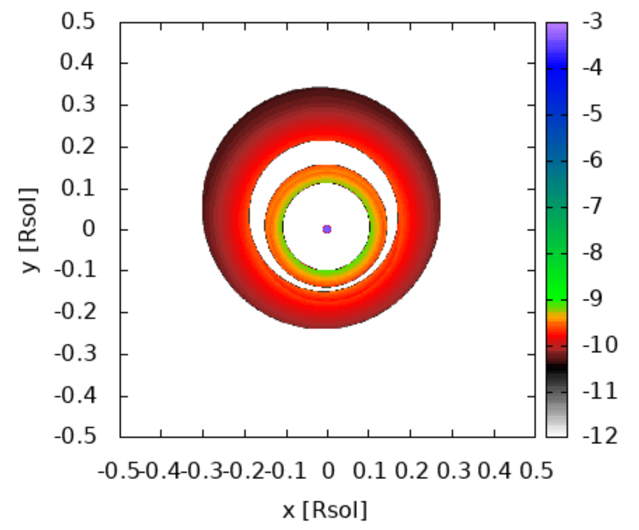
elliptical gas disk

Shellspec (Budaj&Richards 2004)
RT in moving medium, LTE
-Elliptical disk model
-continuity equation preserved
-radial temperature gradient
-gravitational redshift of the star
-precession=>variability (expected from GR)

2 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
prograde precession P=3.83 yr
Mass=8x10^{-11} M_Earth



elliptical gas disk

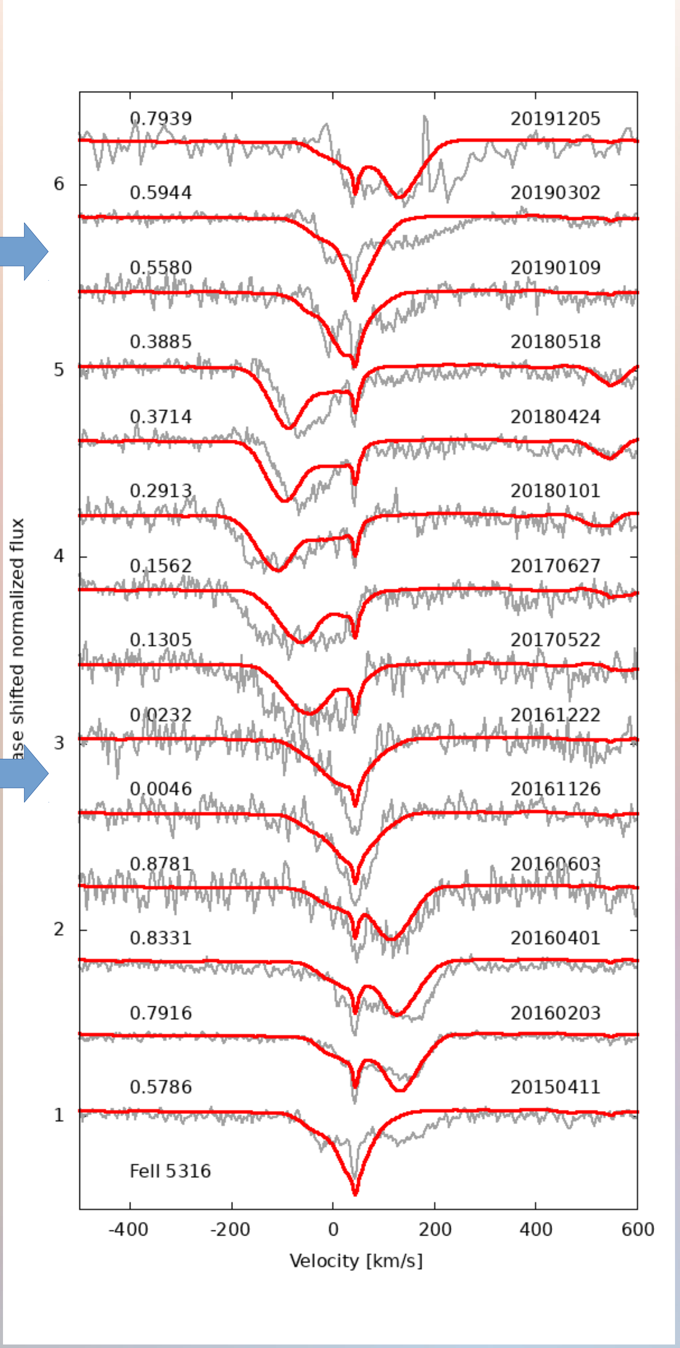
Previous models by Cauley et al. 2018, Fortin-Archambault et al. 2020:
14 eccentric rings, retrograde precession, vertical temp. gradient, Mass=10^{-5}M_Earth, fits UV spectra well…

Our model
Pros:
resolves most of the problems of the previous models + fewer number of free parameters, prograde precession…

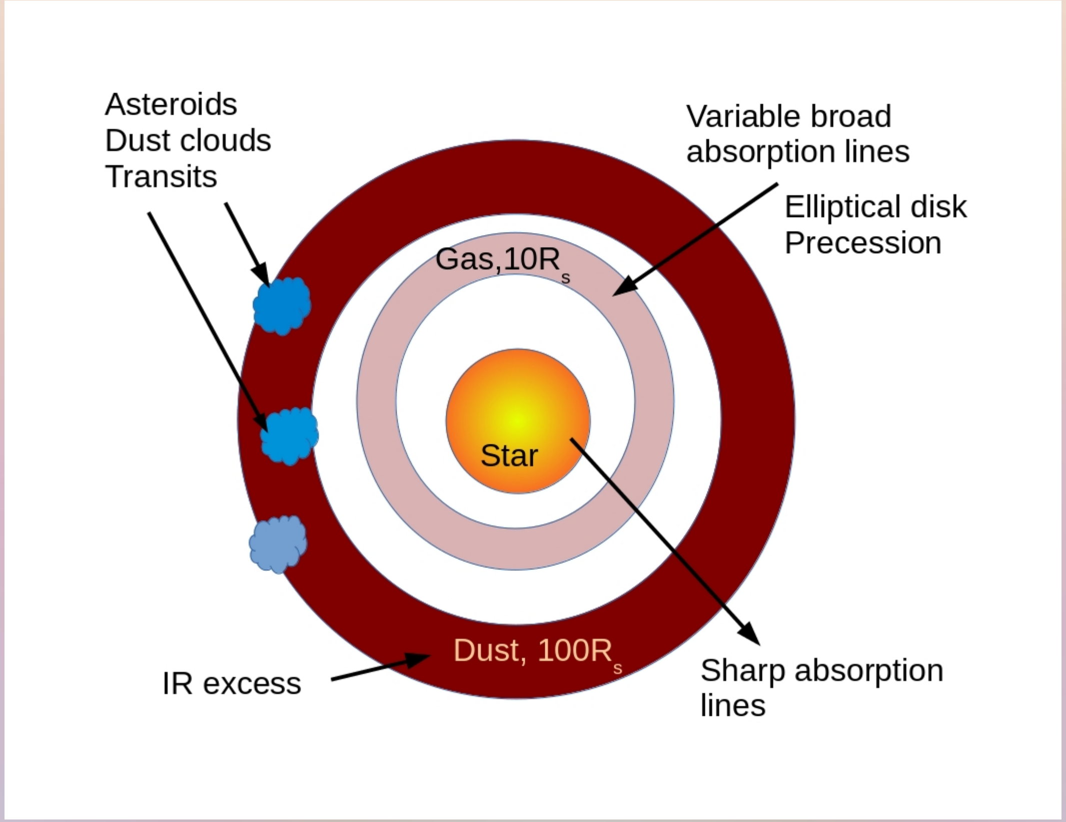
Cons:
-fits only a narrow part of the spectrum
-no vertical temperature gradient
?-Mass=$8x10^{-11}$ M_Earth, 5 orders of mag. smaller than previous models !

periastron

apoastron



WD1145



Schematic picture of the system
(Maliuk et al. in prep.)

Exo-comets

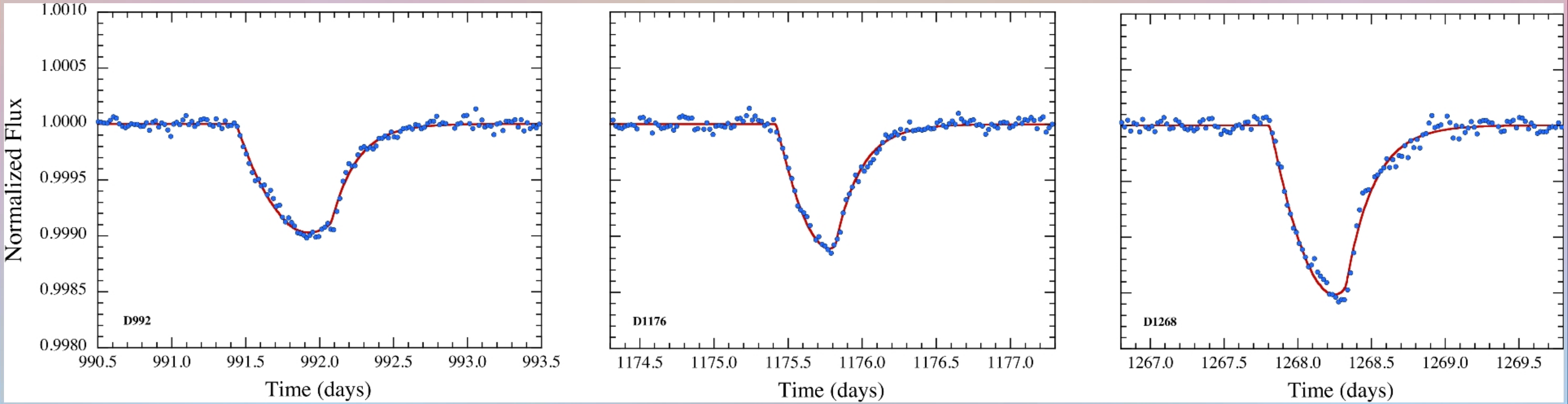
Rappaport et al. 2018
Kepler
KIC 3542116, F2V
-three deeper transits 0.1%, last 1 day
-three shorter and shallower transits
KIC 11084727: similar to KIC3542
one event
No periodicity in either case

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



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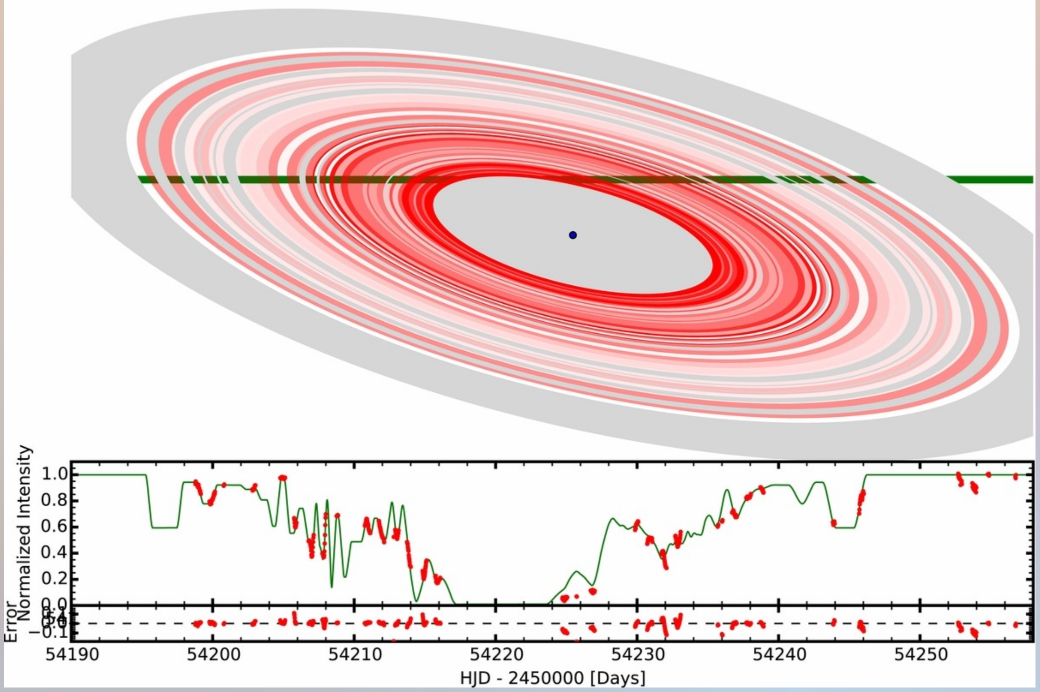
Exo-rings, exo-moons?

-hypothetical objects, indirect evidence
-problem: radii of some exoplanets are quite large and imply average densities of about 0.1 g/cm3
-exo-rings might be a solution (Akinsanmi et al. 2020, Piro & Vissapragada 2020)
-deep asymmetric eclipses:
EPIC2043 Rappaport et al. 2019
V928Tau van Dam et al. 2020
EPIC2202 van der Kamp et al. 2022

Kenworthy & Mamajek 2015
1SWASP J140747.93-394542.6
-K5, 16 Myr old star in the Sco-Cen OB association
-M=0.9 M_Sun
-V=12.3mag
-one transit of a giant ring system orbiting an unseen companion (2007)
-transit duration 56 days, >95%deep

-37 rings up to 0.6 au
-gaps probably carved by satellites
-mass of rings about 1 M_Earth
-green line =star
-orbital period >10yr
-J1407b is probably a brown dwarf, possibly an exoplanet



TESS and PLATO will discover more objects of this kind and we are entering a new era of the exploration of not only exoplanets but also small bodies of extrasolar systems.

Thank you!

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