Leibniz-Institut für Astrophysik Potsdam

The physics of exoplanets and their host stars revealed by X-ray observations

Katja Poppenhaeger (AIP Potsdam & Potsdam University)

Symposium: 25 Years of Science with Chandra

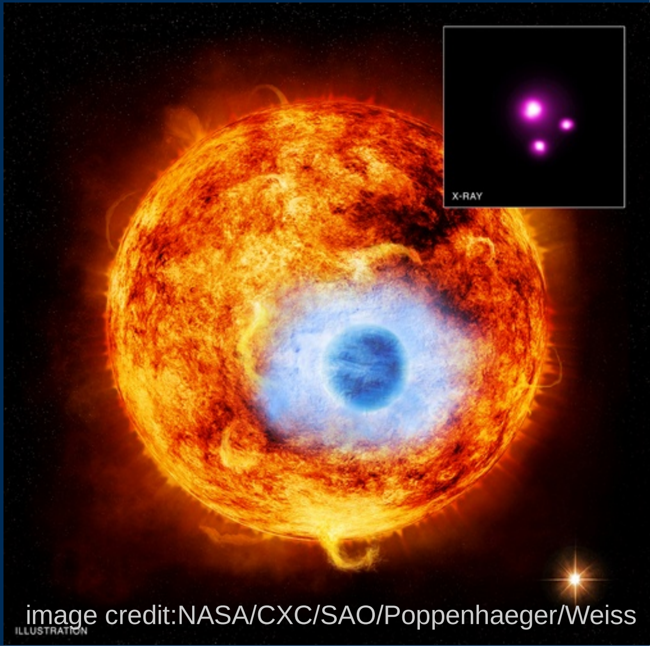


image credit:NASA/CXC/SAO/Poppenhaeger/Weiss

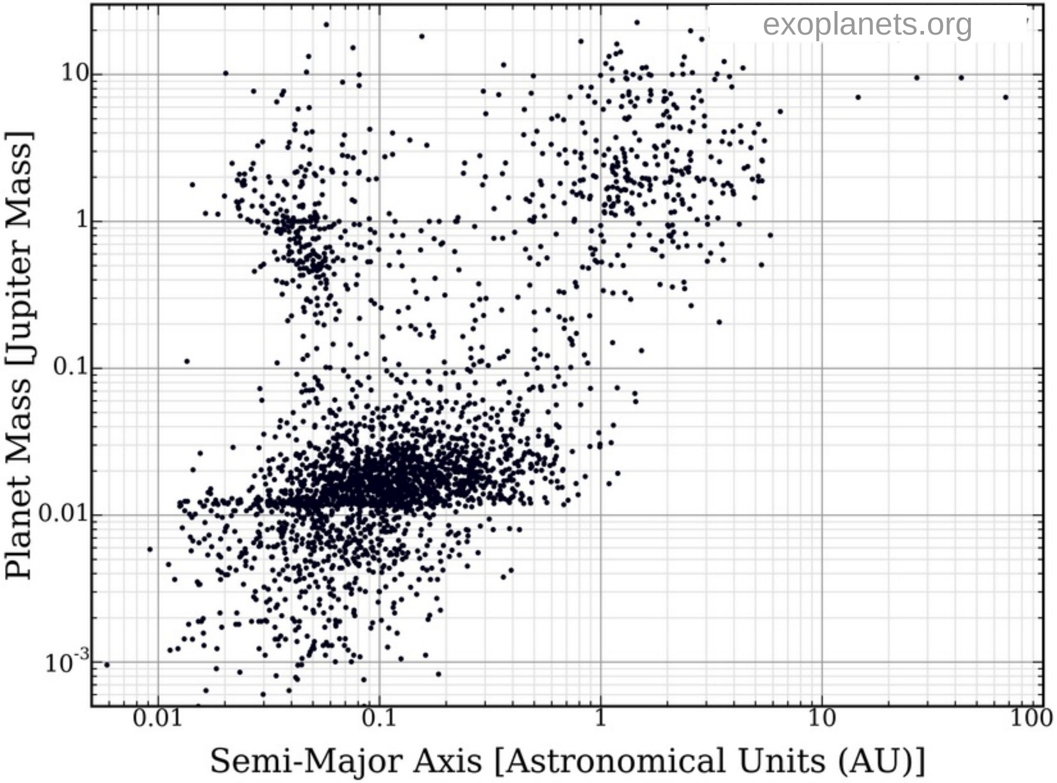
Exoplanets and their host stars as X-ray objects

Stars: wide variety of X-ray emission properties, but... exoplanets?

Some categories:

- X-ray emission from interesting physics in star-planet systems:
  - tidal star-planet interactions
  - magnetic star-planet interactions
  - „exotic“ accretion
- X-ray and UV environment created by host stars as drivers for exoplanetary atmospheric erosion
- X-ray shadows (exoplanet atmospheres as X-ray absorbers)

What stars are we talking about in star-planet systems?



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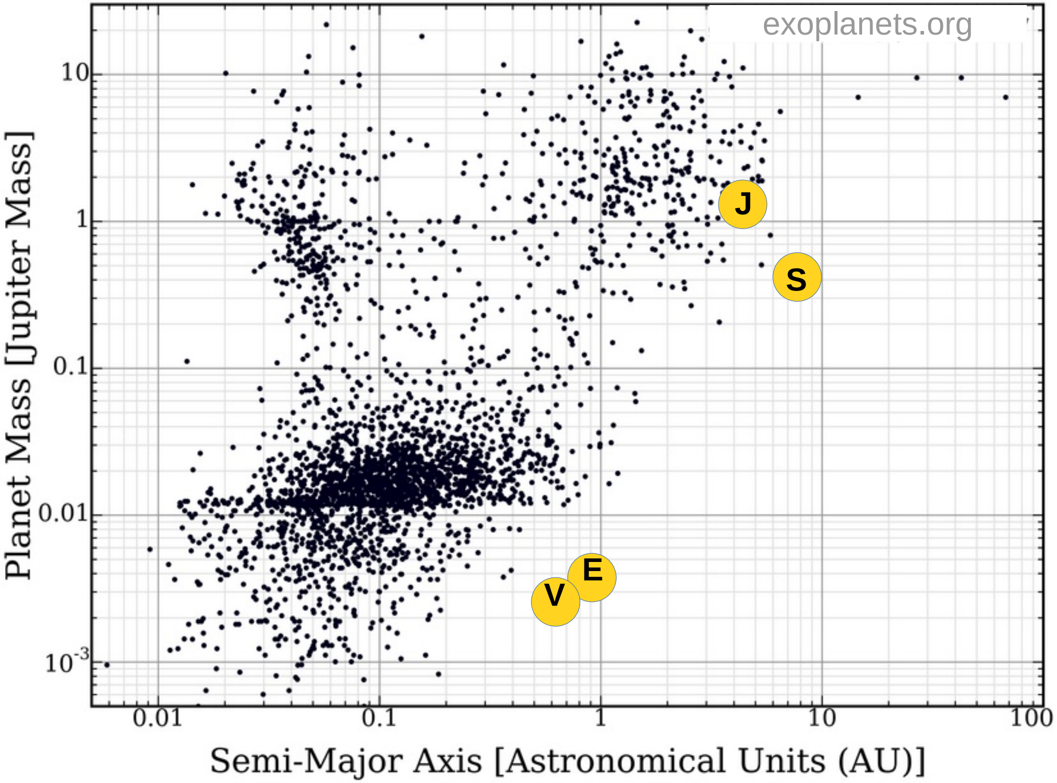

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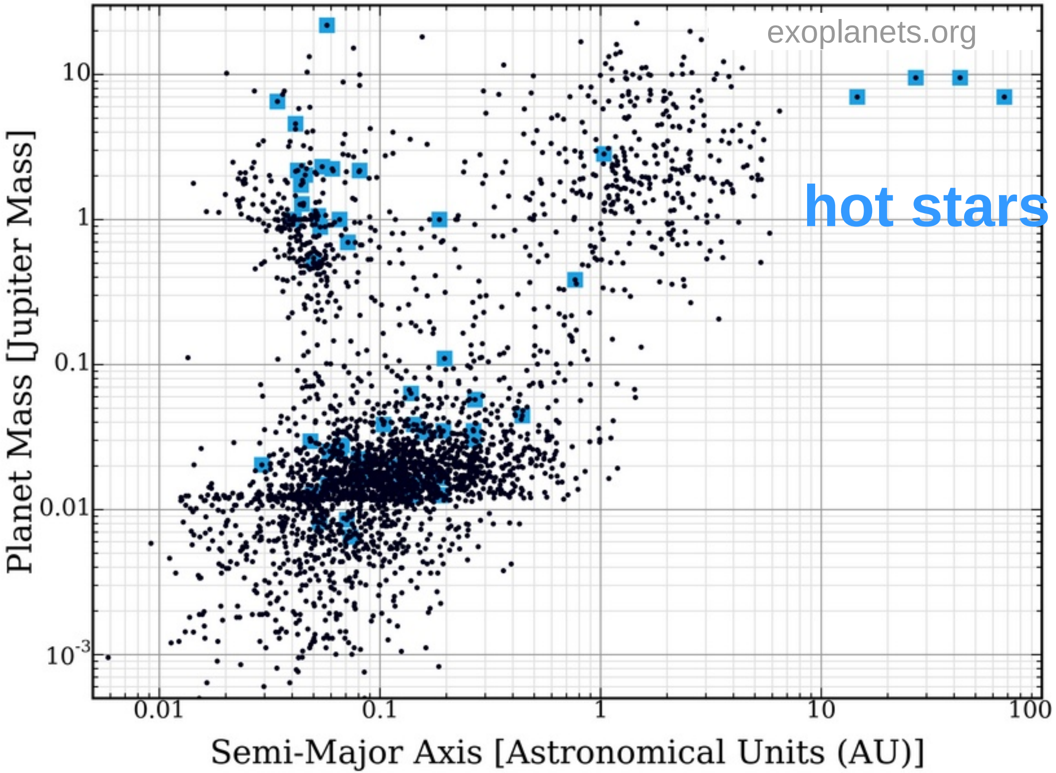

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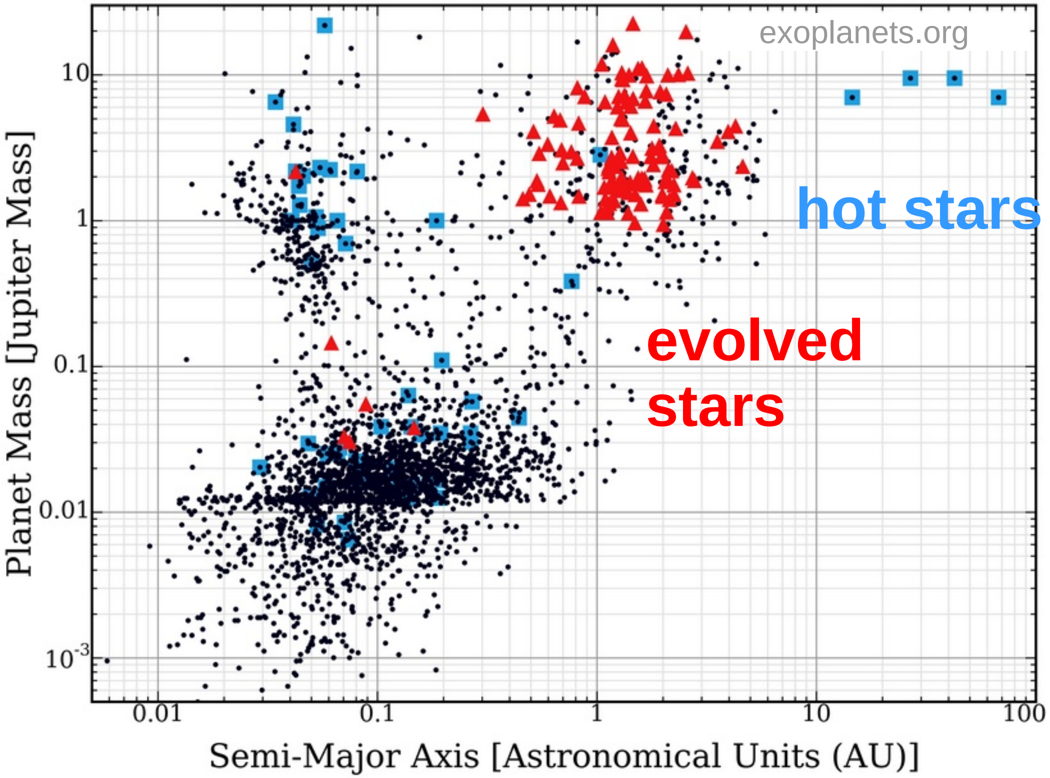

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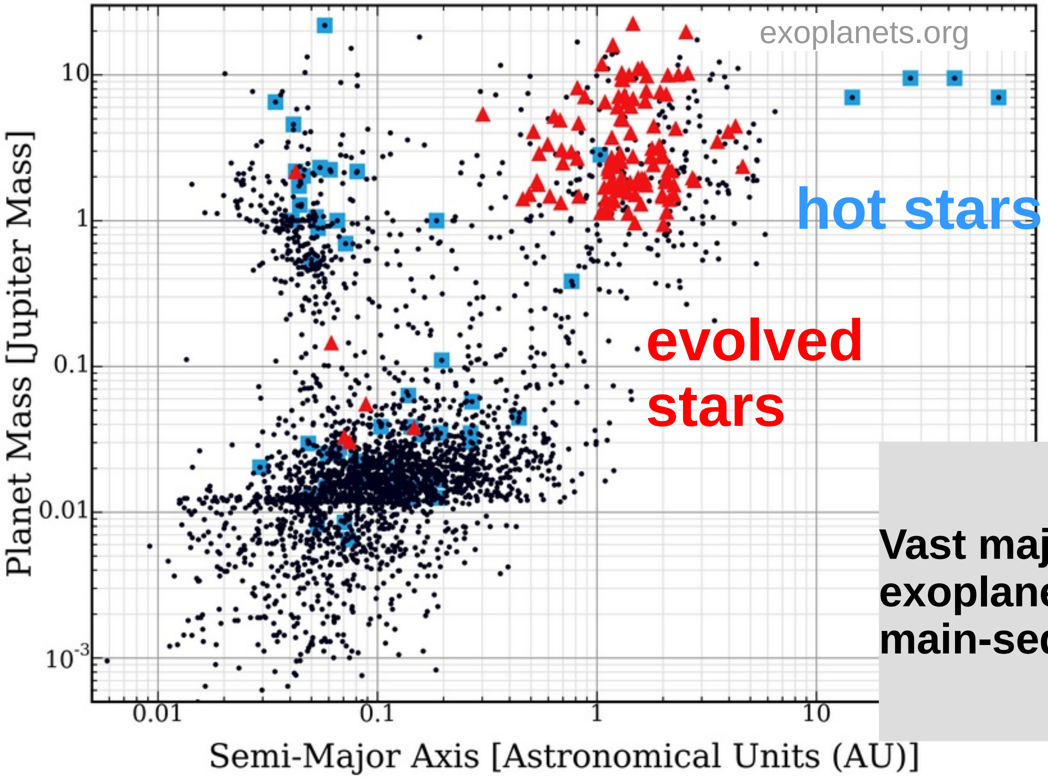
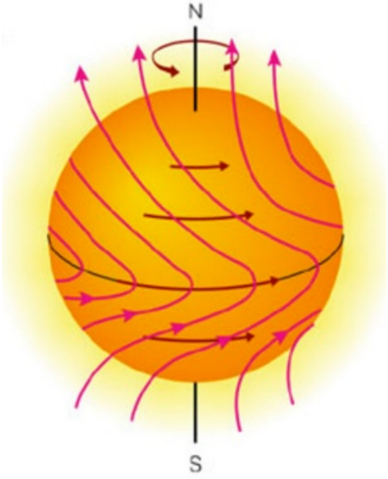


Vast majority of known exoplanets have cool main-sequence host stars!

What’s the X-ray emission process of planet host stars as a „background candle“?

- Most exoplanet host stars are low-mass main-sequence (ish) stars -> more or less Sun-like
- X-ray emission from a corona, ultimately fuelled by stellar rotation through a dynamo operating inside the star.
- Magnetic braking is relevant: angular momentum loss because star sheds a magnetized wind.



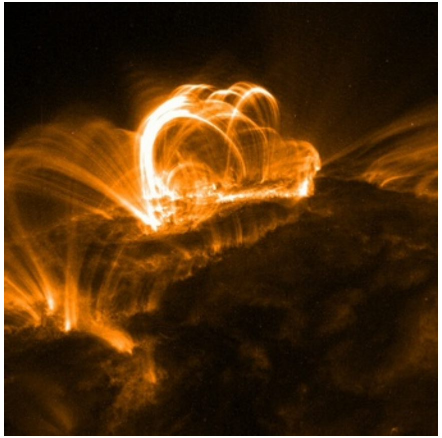
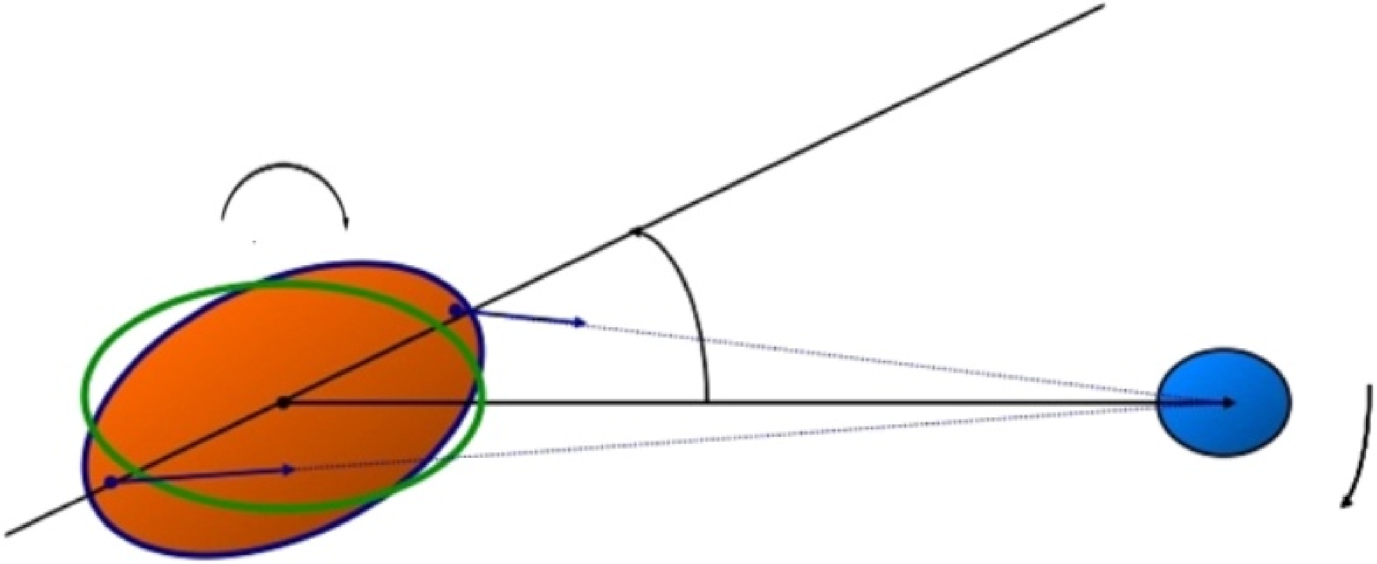


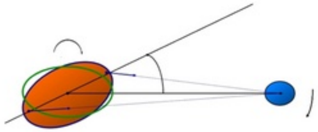
image credit: A. Wesley, NASA

Star-Planet Interaction (tidal)



Mathias & Remus (2013), see also Lanza & Mathis (2016)

Star-Planet Interaction (tidal)



What to observe?

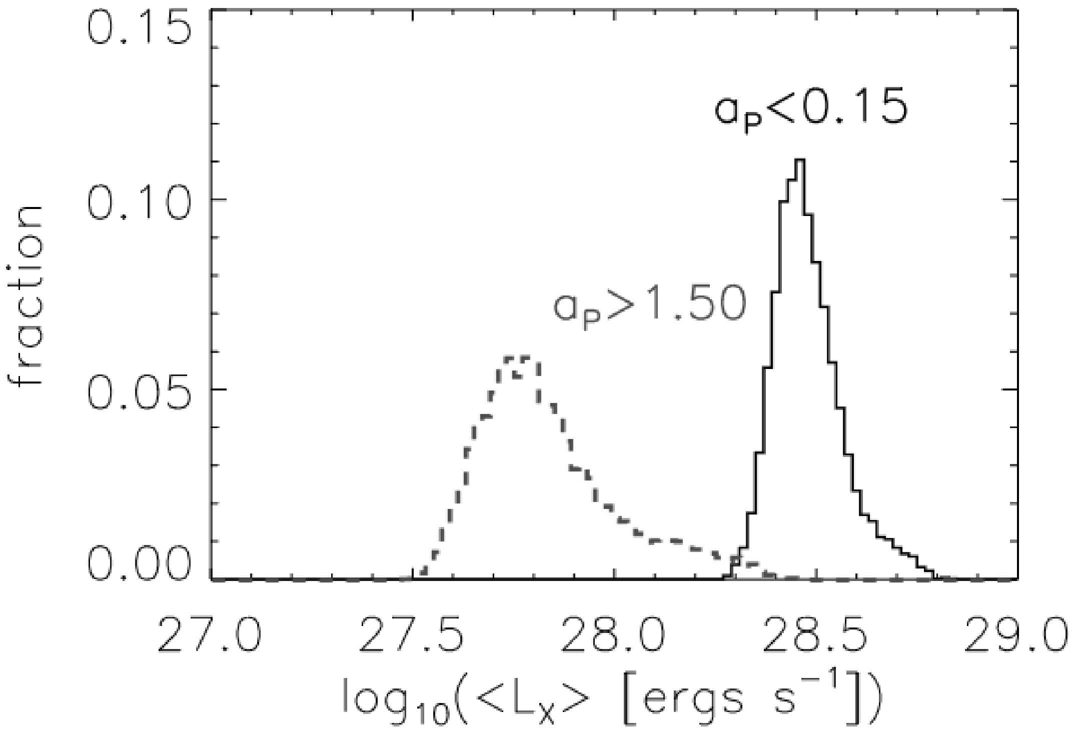
Star: spin-up compared to regular evolution and therefore elevated overall activity (but difficult to judge in absence of absolute stellar ages)

Planet: shrinking orbit

See for example:

Kashyap et al. 2008;
Poppenhaeger et al. 2010;
Brown et al. 2011;
Poppenhaeger & Wolk 2014;
Miller et al. 2015;
Penev et al. 2016;
Maciejewski et al. 2016;
Strugarek et al. 2017;
Turner et al. 2021;
Ilic et al. 2022, 2023

Star-Planet Interaction: X-ray activity of planet host stars



You can demonstrate observationally that stars with close-in planets are more active and faster rotating than ones with far-out planets.

But why?

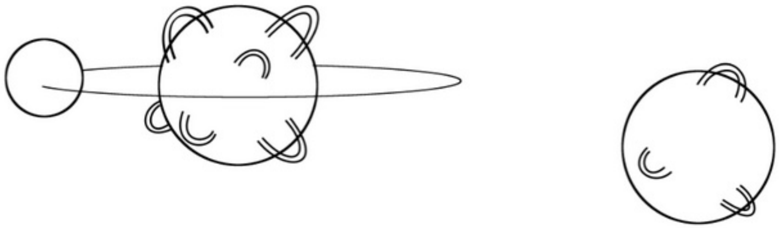
Planet detectability is a function of stellar activity! (More difficult when more active)

Kashyap et al. 2008; see also Poppenhaeger et al. 2010, Miller et al. 2015

Star-Planet Interaction (tidal)

Test, eliminating planet detection bias:

Do stars with Hot Jupiters have higher X-ray activity than their co-eval stellar companions?



early results: see
Poppenhaeger & Wolk (2014)

Star-Planet Interaction (tidal)

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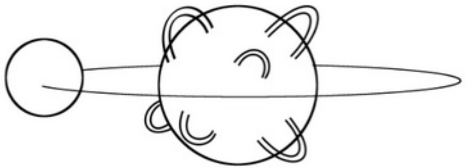
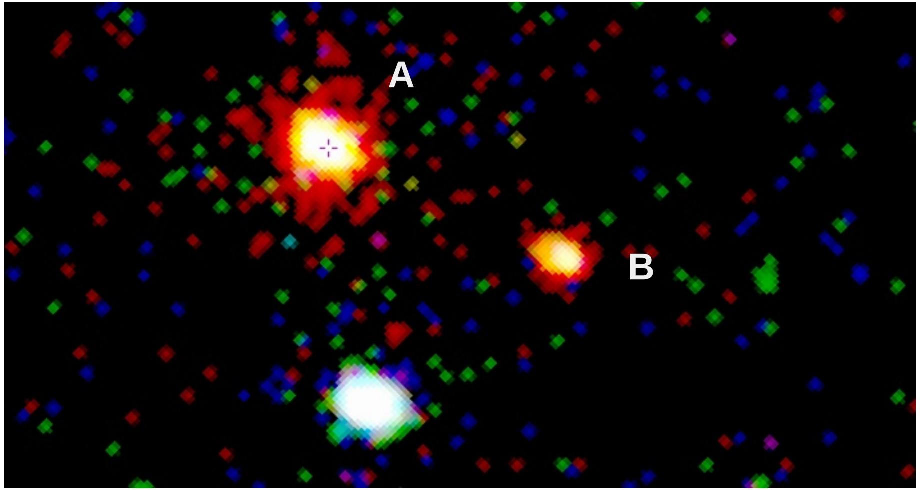




Chandra's view:

HD 189733 A (with Hot Jupiter)
+ HD 189733 B (no planet known)
+ background object

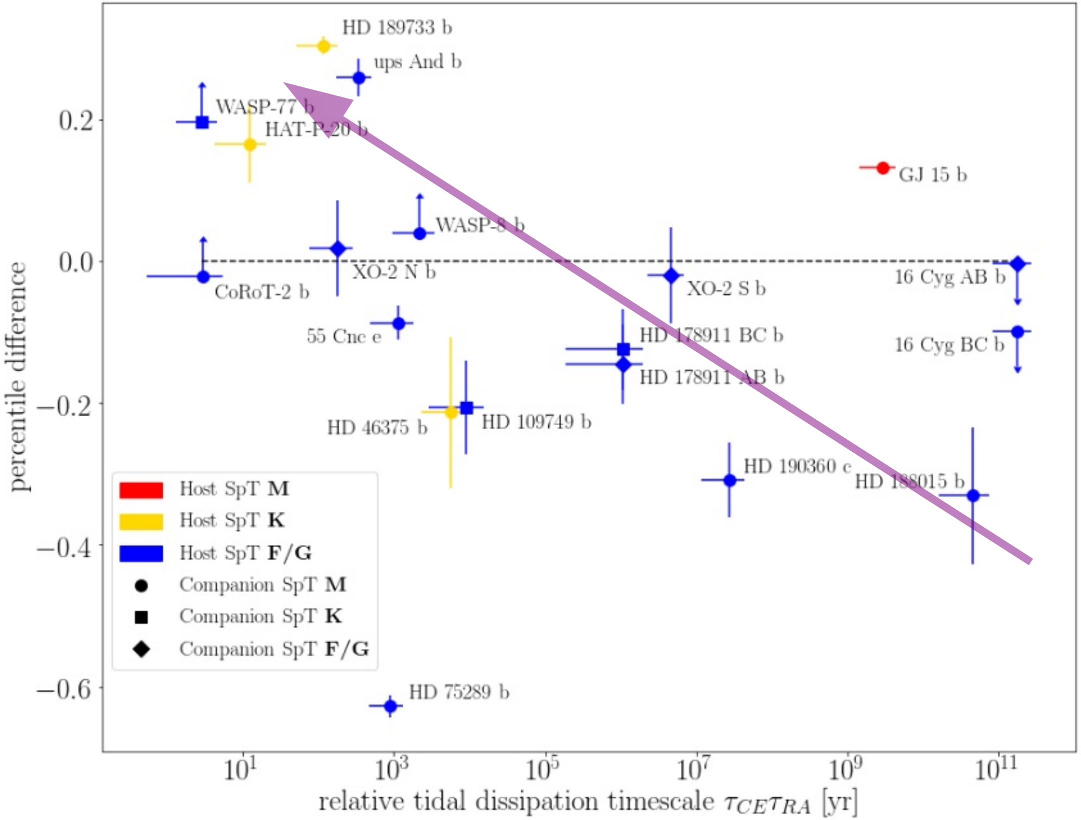
early results: see
Poppenhaeger & Wolk (2014)

Star-Planet Interaction (tidal)

Test, eliminating planet detection bias:

Do stars with Hot Jupiters have higher X-ray activity than their co-eval stellar companions?

Yes!



Ilic, Poppenhaeger & Hosseini (2022)

Star-Planet Interaction (magnetic)

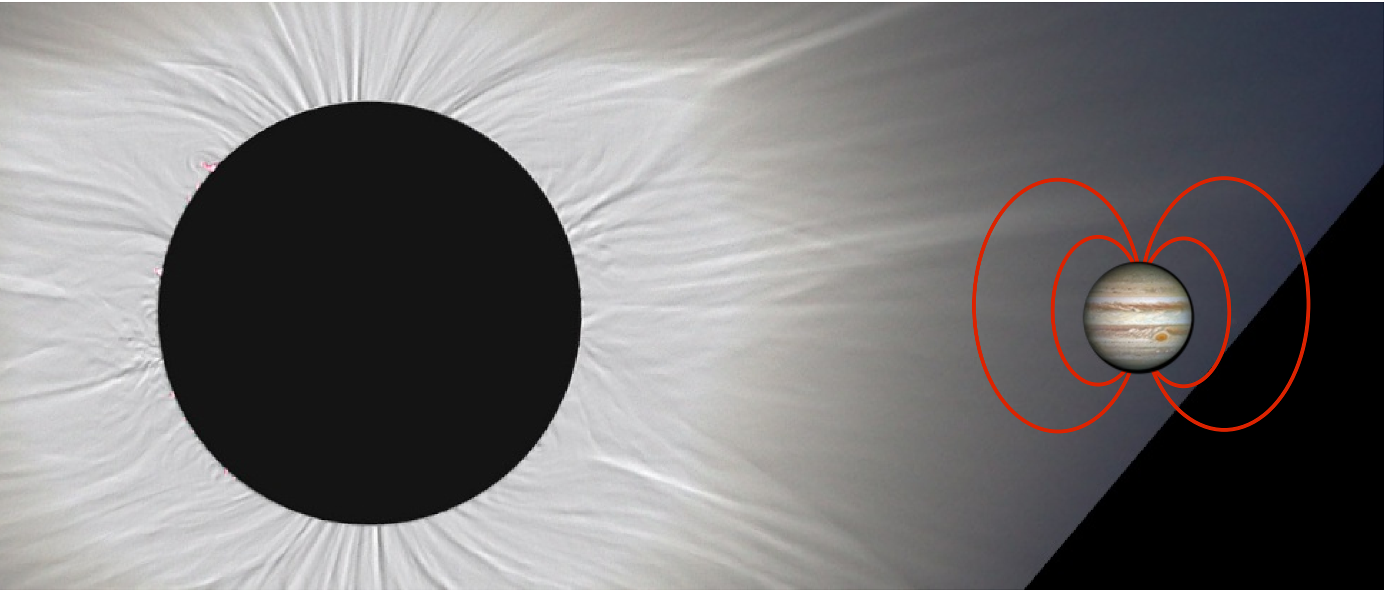


image credit:Druckmüllerová & Druckmüller; Pasachoff et al. (2008)

Star-Planet Interaction (magnetic)

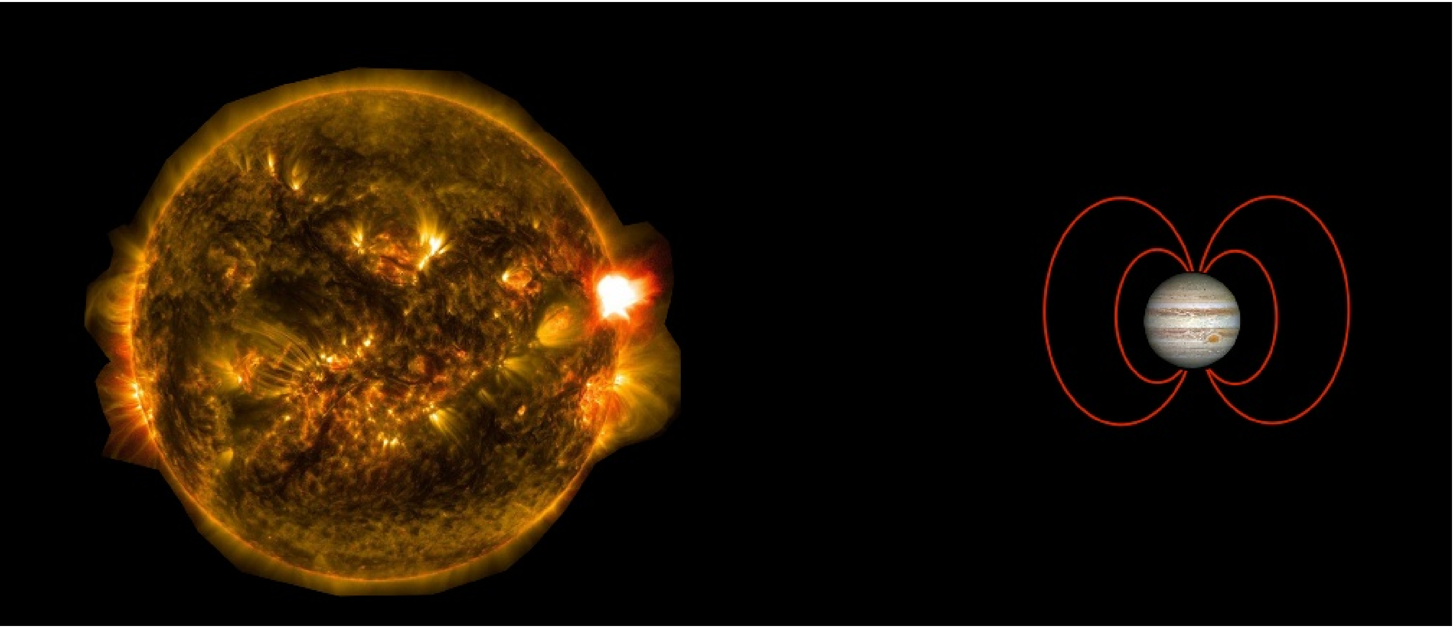


image credit:NASA, ESA

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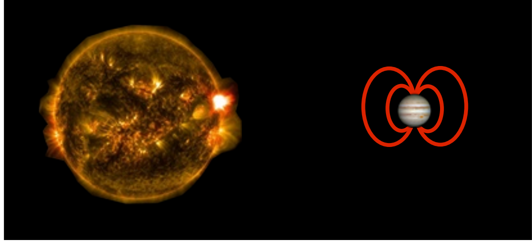


What to observe?

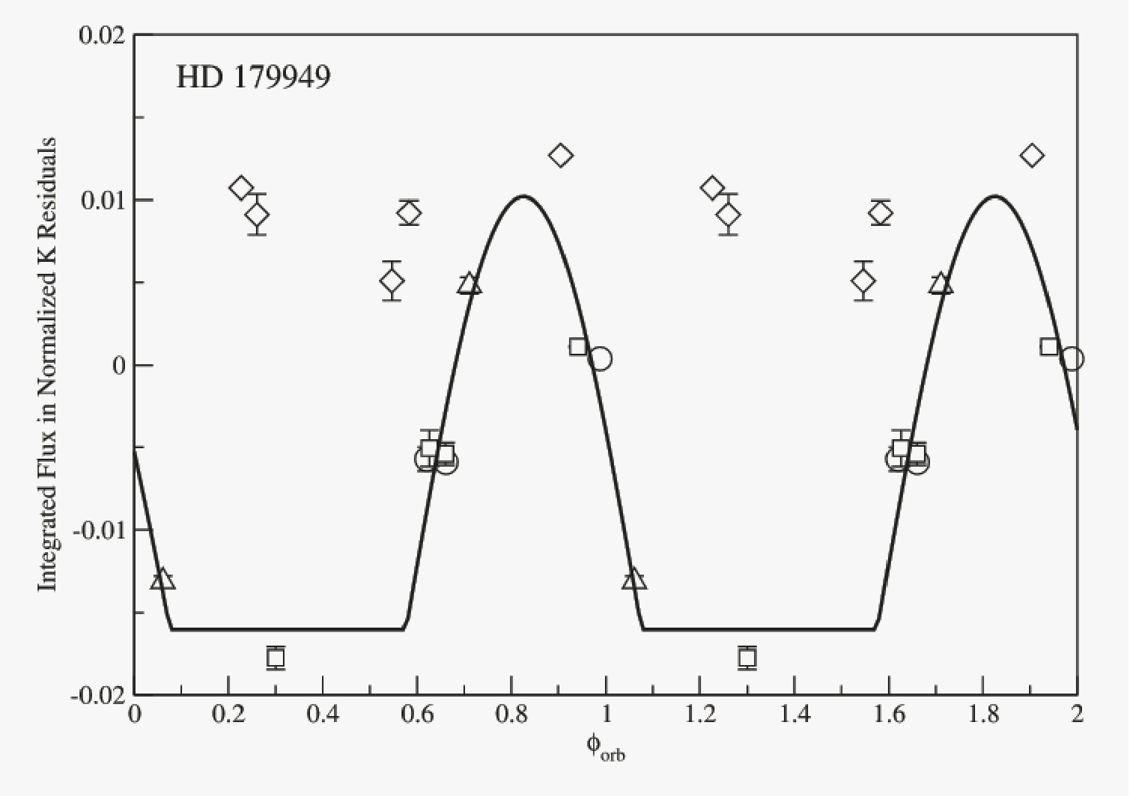
Episodic activity features that are different from standard stochastic activity of star

Look for planet-related periodicities!

See for example:

Shkolnik et al. 2005, 2008;
Lanza 2008, 2009;
Fares et al. 2010;
Poppenhaeger et al. 2011;
Covino et al. 2013;
Strugarek et al. 2014;
Maggio et al. 2015;
Cauley et al. 2019;
Vedantham et al. 2020;
Ilin & Poppenhaeger 2022;
Klein et al. 2022;
Pineda & Villadsen 2023

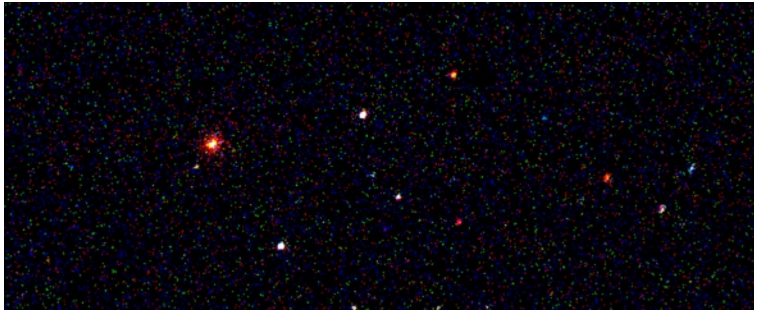
Star-Planet Interaction (magnetic): classic work in optical Ca II H&K



Modulation of stellar activity, seen in chromospheric emission lines, sometimes in sync with planet's orbit.

Shkolnik et al. (2005)

Star-Planet Interaction (magnetic): same star observed in X-rays

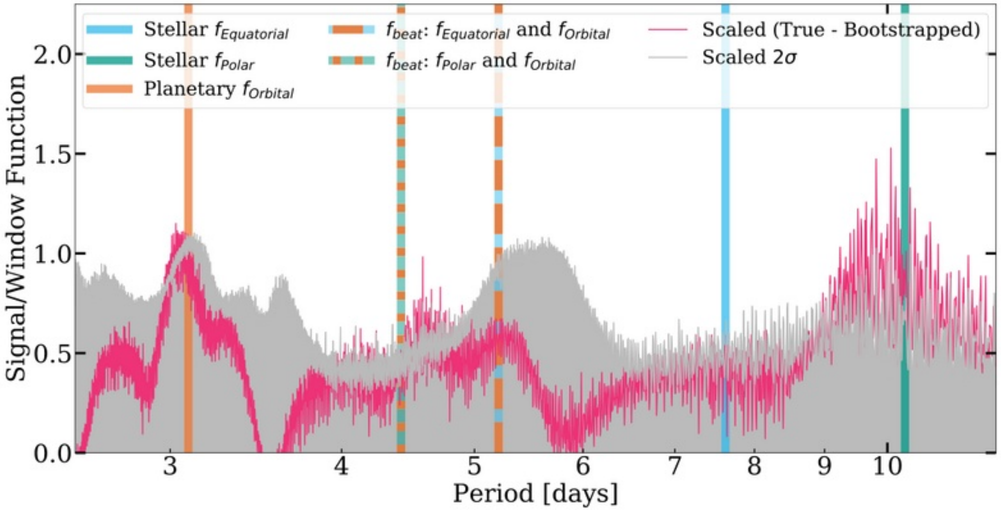


X-ray modulation should be stronger then Ca II modulation.

Combined Chandra + XMM + Swift analysis:

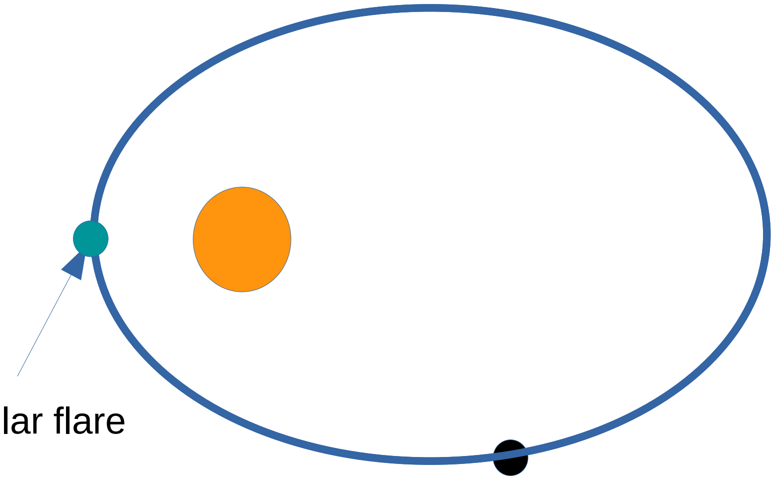
star shows X-ray periodicity signals at stellar rotation period, planetary orbital period and beat period.

Acharya et al. (2023)



Star-Planet Interaction (magnetic): planets in eccentric orbits

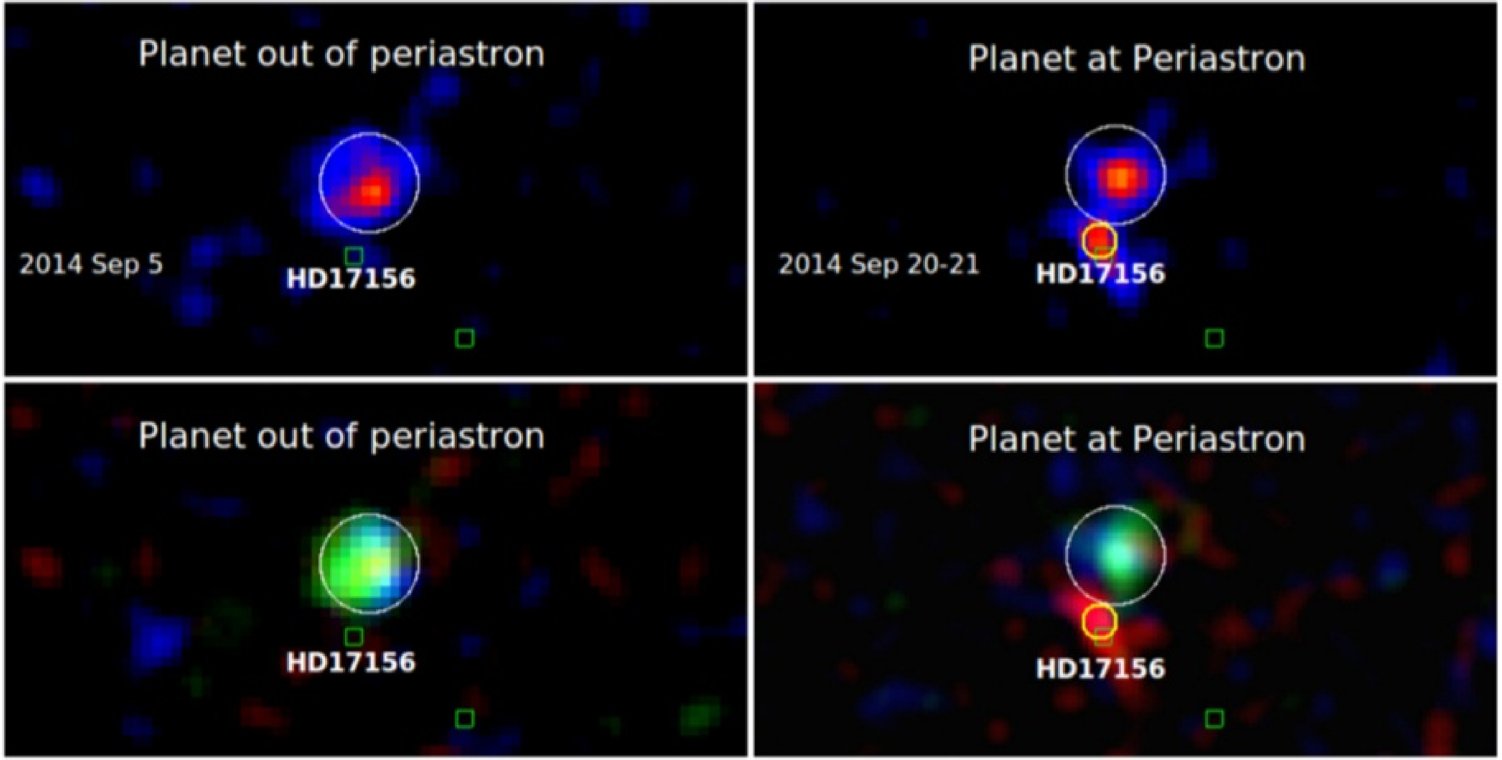
star + planet:



periastron: stellar flare
triggering

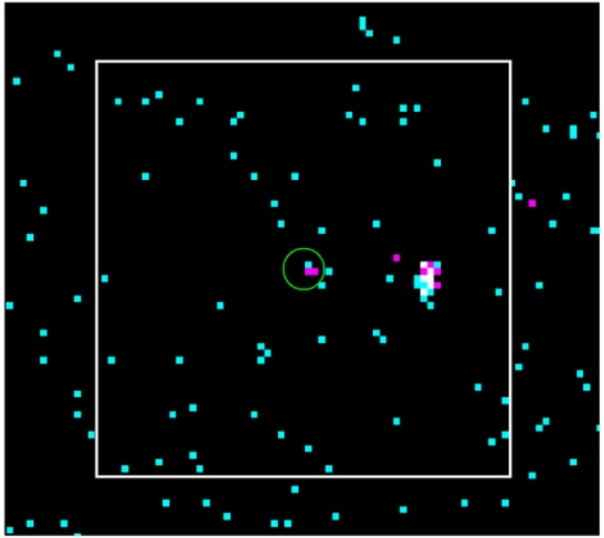
This should depend on
the planet's magnetosphere!

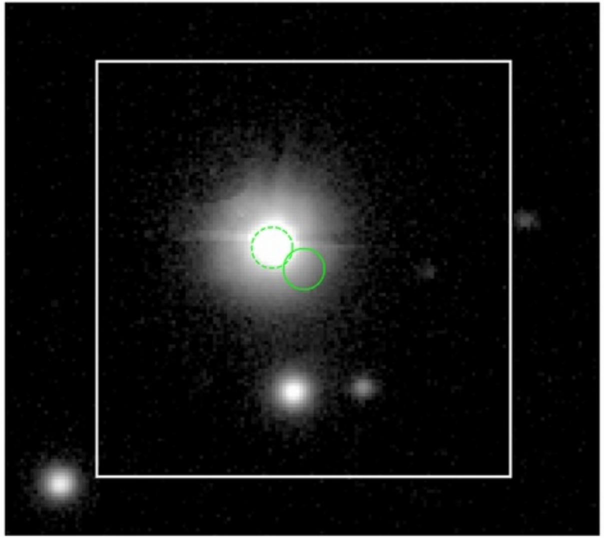
Star-Planet Interaction (magnetic): planets in eccentric orbits

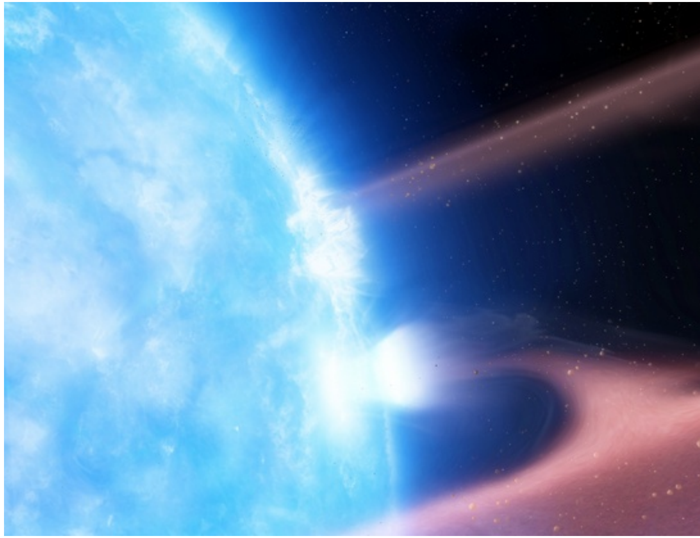


Maggio et al. (2015)

X-rays from planetary accretion onto a white dwarf





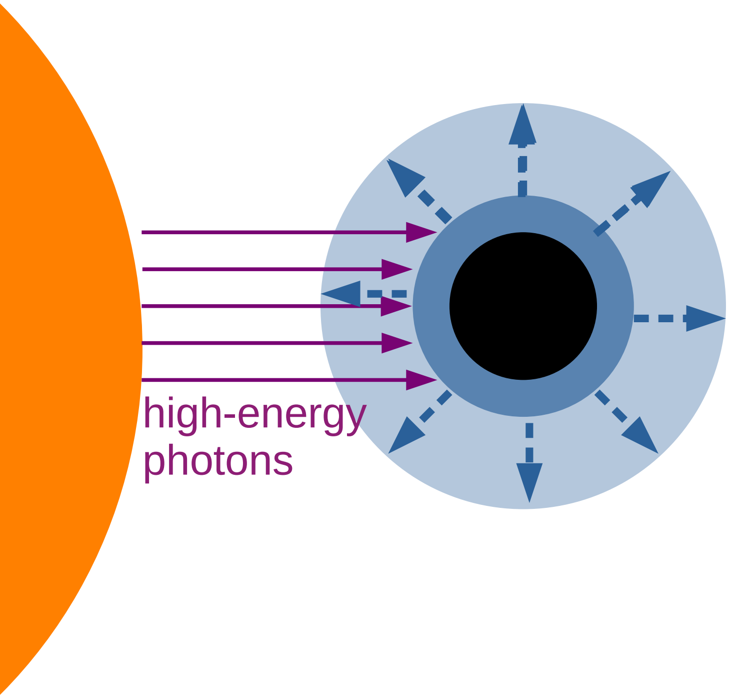


Chandra's ACIS-S finds evidence of accretion of planetary material onto a white dwarf.

Cunningham et al., Nature (2022)

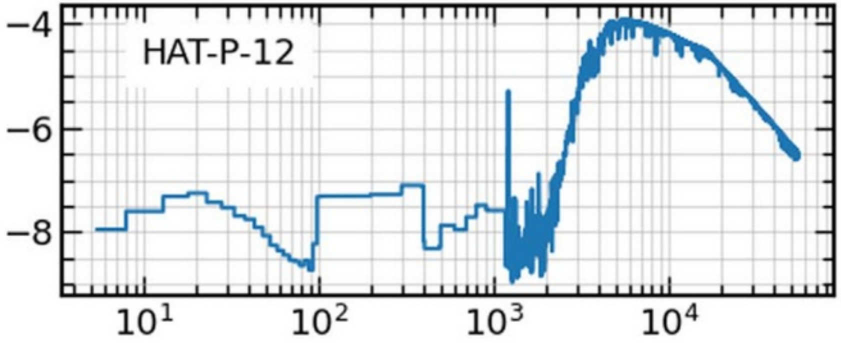
image credit for artist impression:
U Warwick / M. Garlick

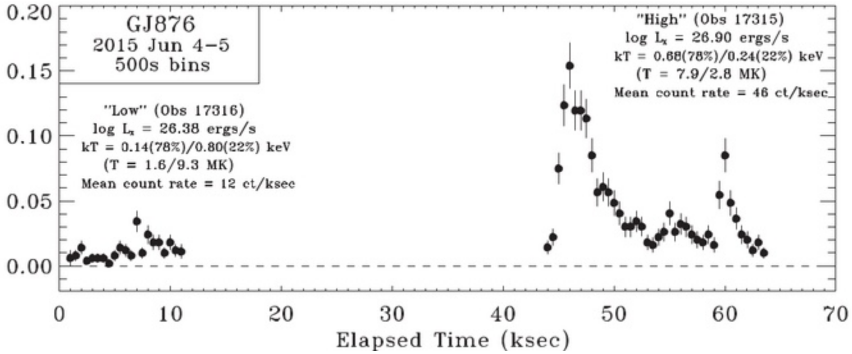
X-ray and extreme-UV driven exoplanet evaporation



- X-ray and extreme-UV photons from the host star are absorbed high up in the exoplanetary atmosphere
- Can drive significant mass loss rates
- Different regimes (energy-limited, core-powered); most relevant for hot Jupiters and Saturns in close orbits: radiation-driven, energy-limited escape
- Evaporating atmosphere clouds can show up as huge absorbers in other wavelengths (UV: hydrogen Ly-alpha, IR: metastable helium triplet)

X-ray and extreme-UV environment of exoplanets

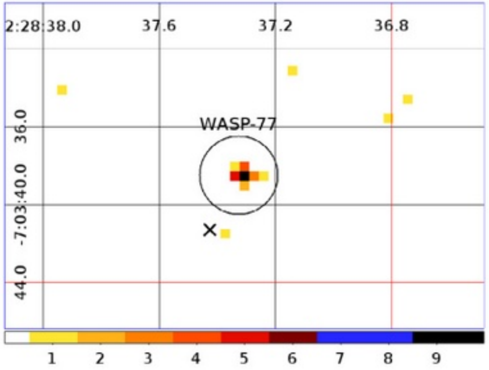


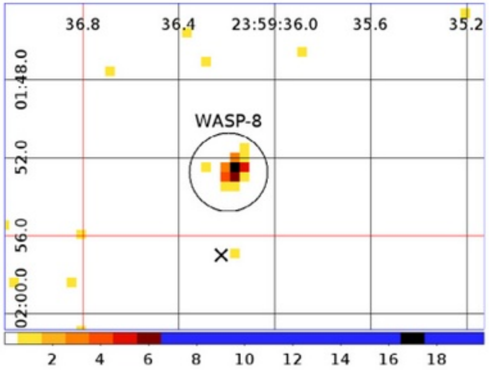


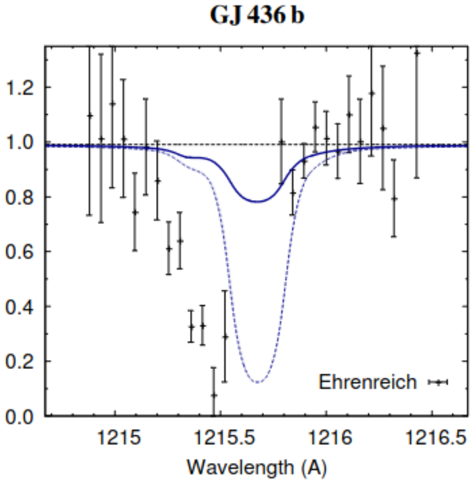
- Characterizing the high-energy environment of an exoplanet important for understanding their atmospheres better
- Successful „industry“ developed in the past years: X-ray + UV (HST) fluxes onto exoplanets
- Not all important parts of the spectrum observationally accessible - EUV!
- Getting the softest X-rays is important to get a handle on the EUV part - see for example HRC observing „trick“ by Jeremy Drake (Drake et al. 2020)

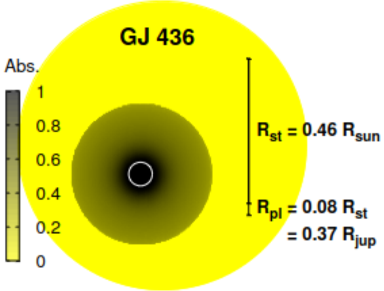
see for example MUSCLES / Mega-MUSCLES projects; France et al. (2016), Froning et al. (2019); Brown et al. (2023)

Atmospheric mass loss & X-rays









- Modelling of evaporating exoplanet atmospheres has made big steps forward in the past decade, fuelled by X-ray observations
- some selected recent examples:
  Salz et al. (2015, 2016)
  Owen & Alvarez (2016)
  Kubyshkina et al. (2018)
  Kubyshkina & Fossati (2021)
  Caldiroli et al. (2022)

plots from Salz et al. (2015, 2016)

X-ray shadows of exoplanet atmospheres

Exoplanet transits with wavelength dependence to probe exoploanet atmospheres.

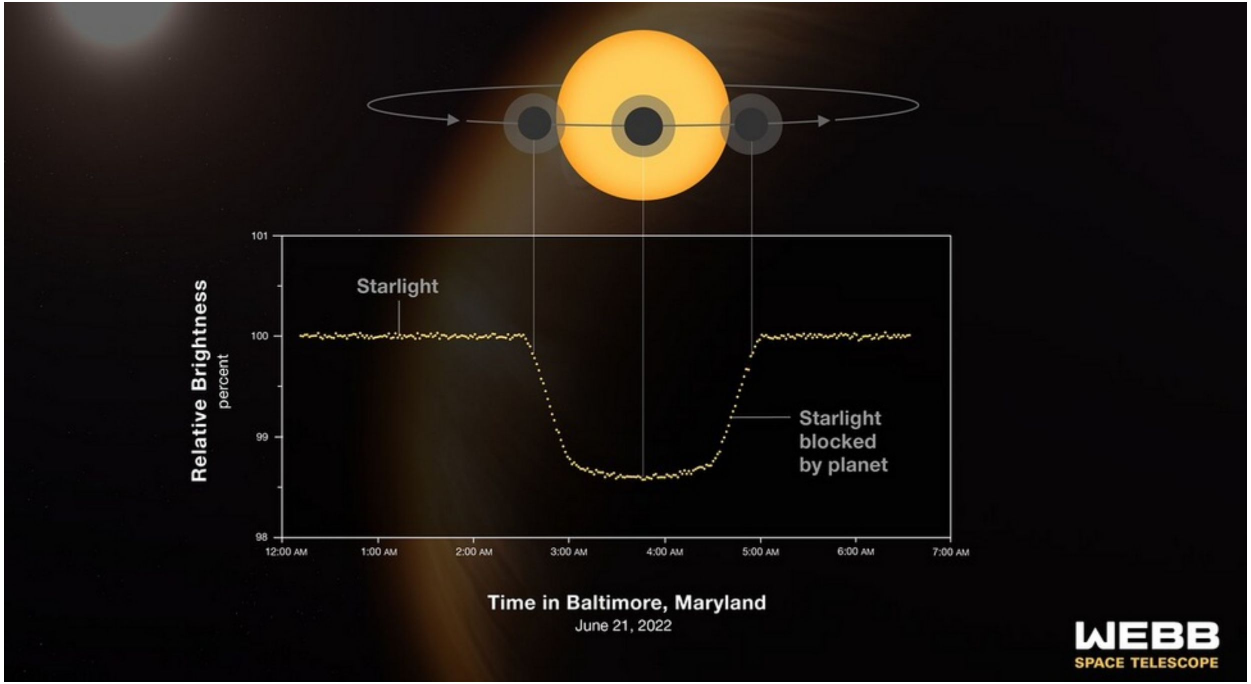
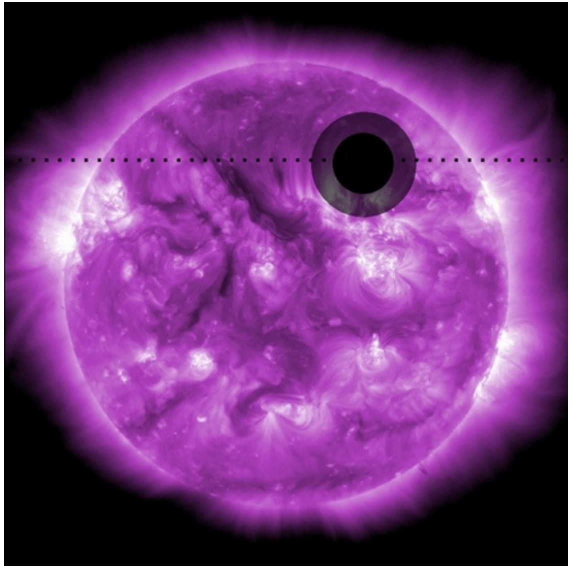
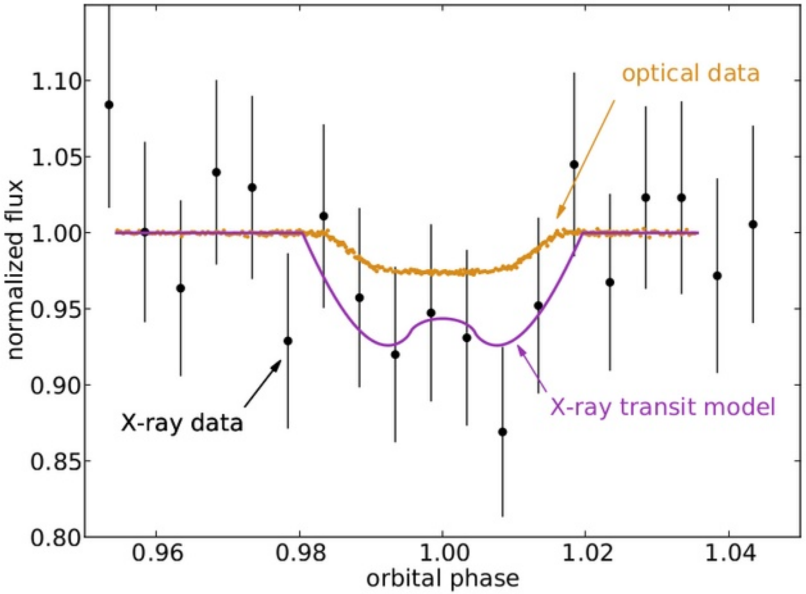


image credit: NASA, ESA, CSA, STScI, and the Webb ERO Production Team

X-ray shadows of exoplanet atmospheres



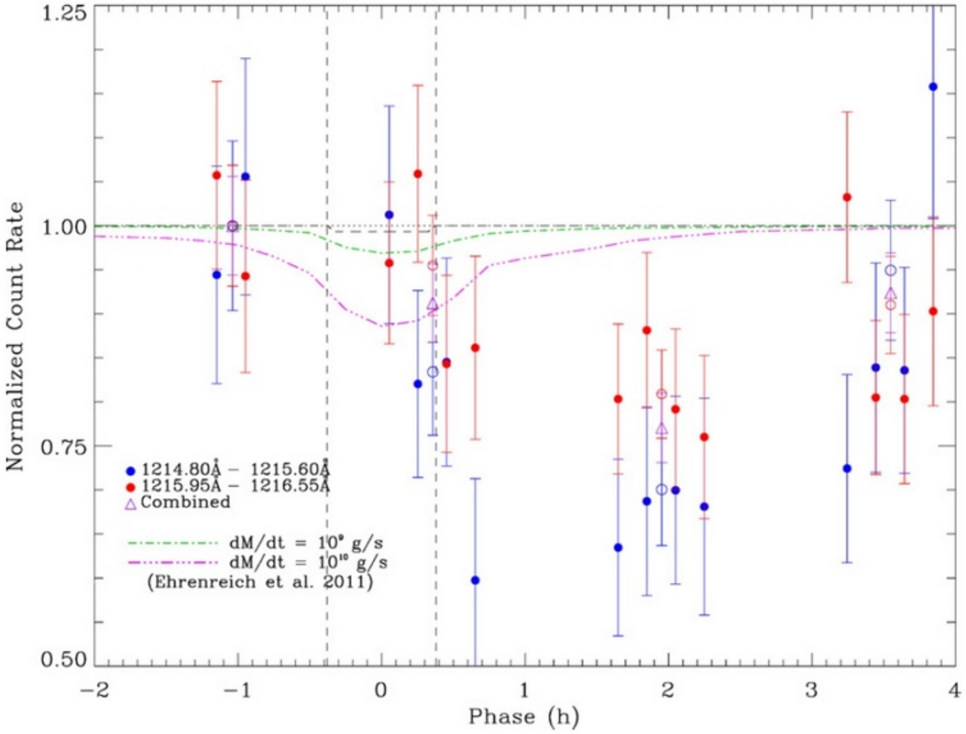
Hot Jupiter HD 189733 b

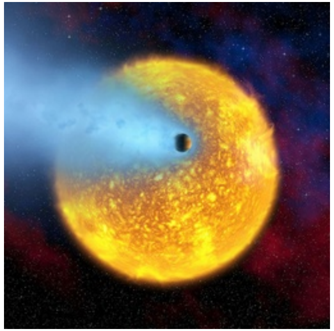


Chandra + XMM data,
X-ray transit depth 6% vs. optical 2.5%

Poppenhaeger et al. (2013)

Evaporation of exoplanet atmospheres in the UV



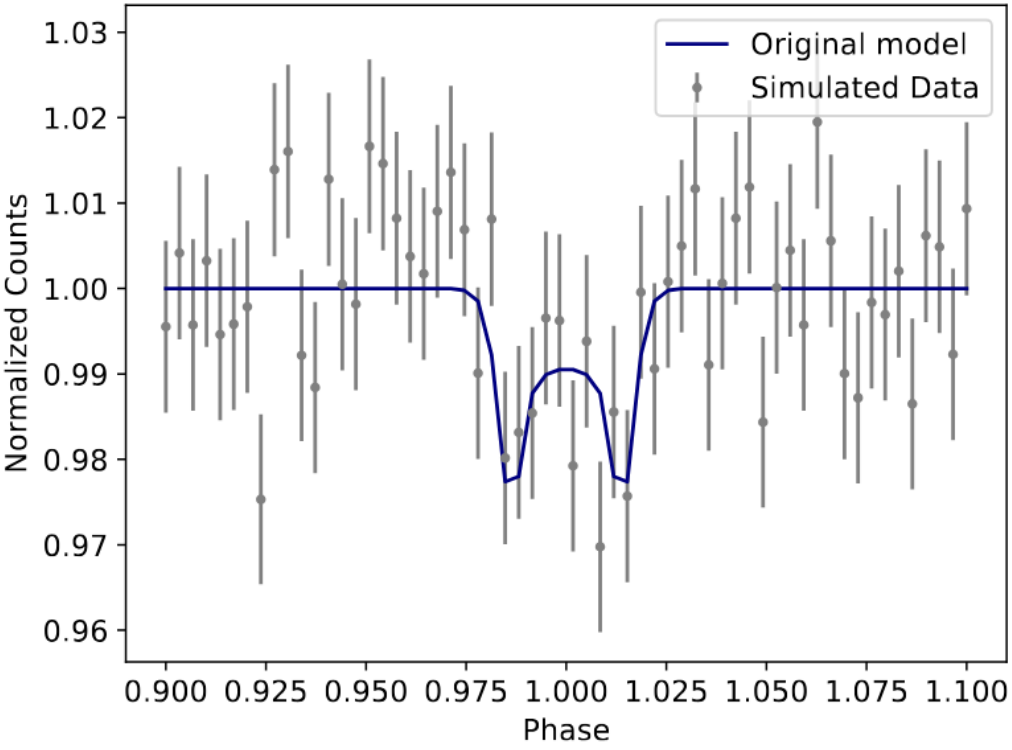


ca. 40% of stellar disk occulted by evaporating tail of small exoplanet (GJ 436 b)

Kulow et al. (2014),
Ehrenreich et al. (2015)

Also: material falling back onto the host star possible, see Pillitteri et al. (2015), Zhang et al. (2023)

X-ray shadows of exoplanet atmospheres - the path ahead with NewAthena



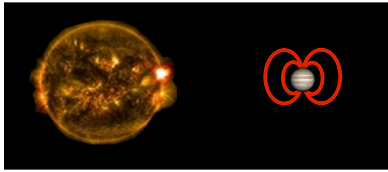
Simulation for shallow X-ray transit of only 2.5%

Cilley, King & Corrales (2024)

Summary: Chandra’s keen X-ray eye on exoplanet systems

Our understanding of exoplanets and their host stars has made huge steps forward in the past 25 years, many of them enabled by Chandra data.

- X-rays have put Star-Planet Interactions are on a solid observational footing: tidally enhanced stellar X-ray activity is evident in the data; more experimental: potentially SPI-triggered flaring for highly eccentric planetary orbits



- Exoplanet evaporation is highly dependent on the stellar X-ray and EUV output and our understanding has massively benefitted from Chandra (and joint HST) observations, which have generated a whole subfield of charaterization of exoplanetary high-energy habitats.

- Exoplanet atmospheres are challenging as targets for X-ray observations for any current X-ray observatory, but thanks to Chandra one solid X-ray transit measurement has been achieved so far. A new, large-effective area X-ray observatory is needed for a systematic study of X-ray transits of exoplanets.