Exoplanet transits in X-rays: a new observational window to exoplanetary atmospheres

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ADS link to paper
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Context

Transit observations allow us to study the atmospheres of exoplanets.

Observations at short wavelengths (UV, X-rays) are sensitive to thin outer layers of the atmosphere which are transparent to broadband optical radiation.

We are interested in the outer atmosphere because it is crucial for planetary evaporation. High-energy irradiation from the host star (X-ray, EUV) is thought to be the main driver for this, so we want to know where this energy is deposited in the planetary atmosphere.

The HD 189733 system

HD 189733 Ab: most nearby transiting Hot Jupiter

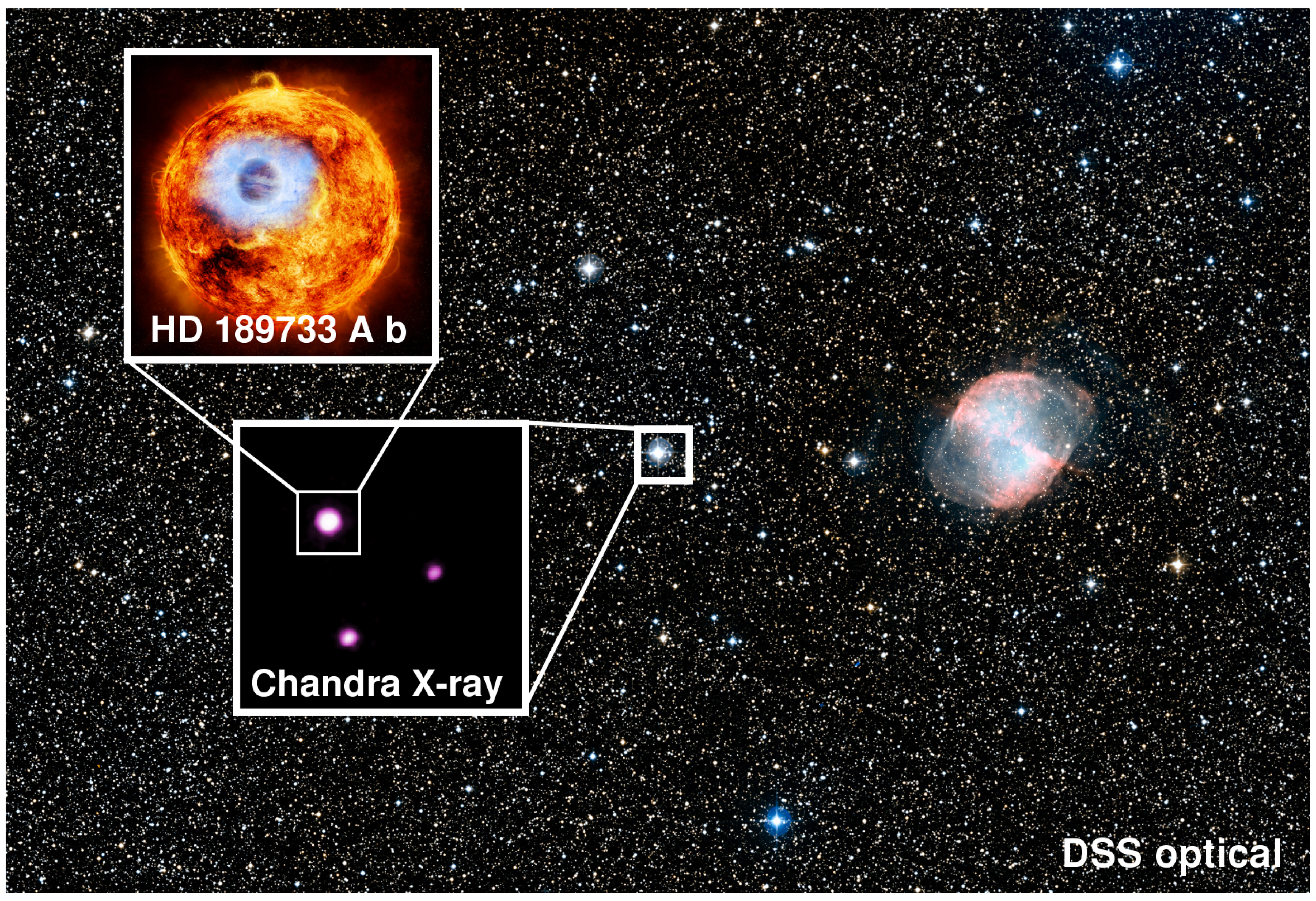
host star: spectral type K1V, has resolved M dwarf companion at $11''$

strong coronal X-ray emission from host star, $L_X = 2 \times 10^{28}\,\mathrm{erg/s}$.

distance to Sun: 19 pc

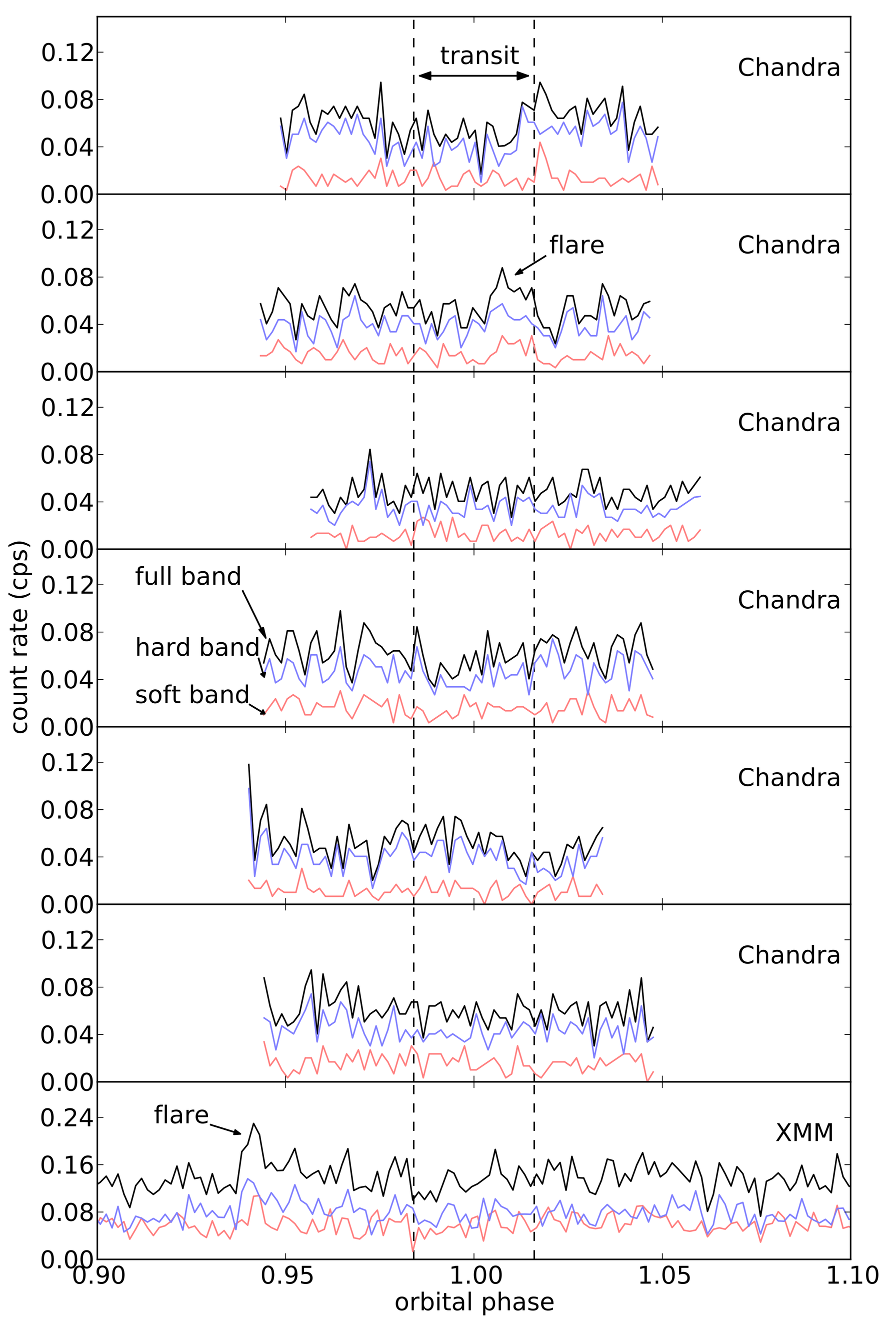
optical transit depth: 2.4%

Hot Jupiter: $M_P = 1.14\,M_{Jup}$, $R_P = 1.138\,R_{Jup}$, $P_{orb} = 2.22\,\mathrm{d}$



picture credit: P. Edmonds and the CfA illustration team, modified by K. Poppenhaeger

Individual X-ray light curves



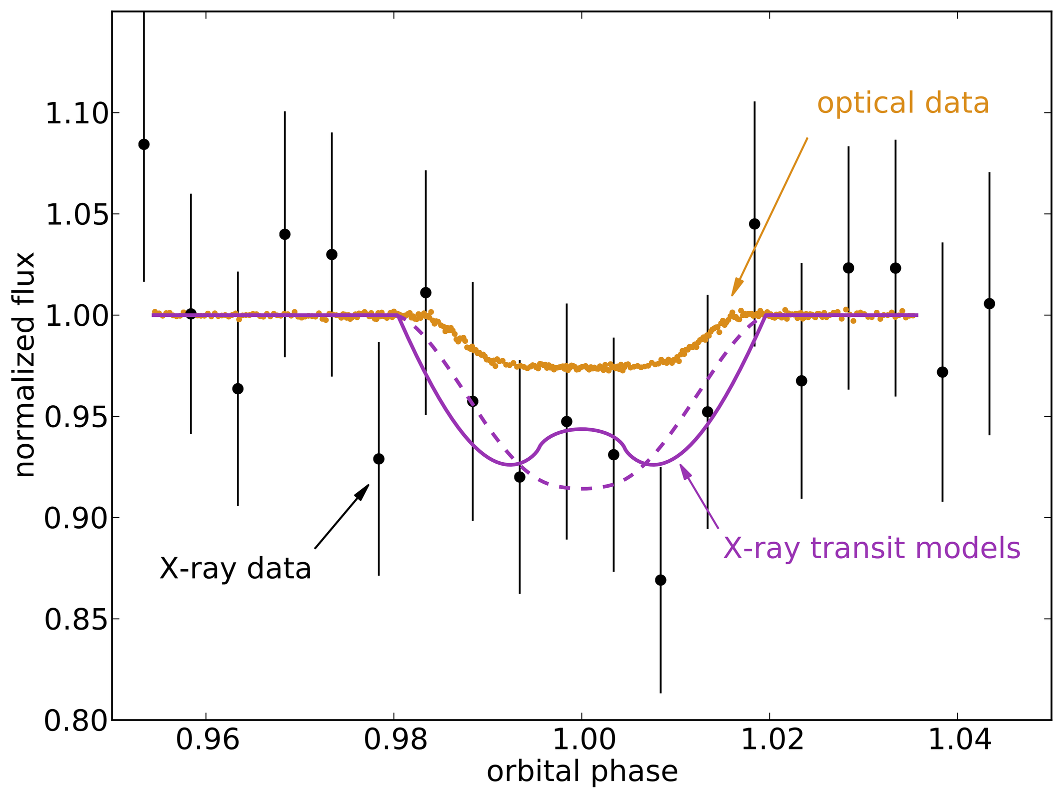
We collected 6 new X-ray transit light curves of HD 189733Ab with *Chandra* and used an archival X-ray transit light curve from *XMM-Newton.*

The transit lasts ca. 2h, while each individual X-ray observation is ca. 6h to cover the out-of-transit levels properly.

Some of the light curves contain small stellar flares, so we did the analysis on (1) all datasets and (2) only the flare-free datasets.

The full band contains photons with energies between 0.1–2 keV (—); soft band = 0.1-0.6 keV (—), hard band = 0.6-2 keV (—).

The X-ray transit



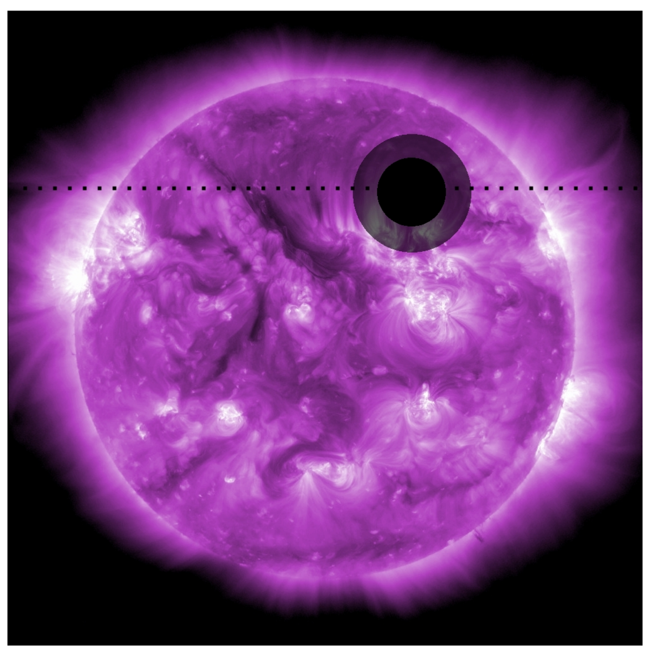
Poppenhaeger et al. (2013)

We co-added all X-ray transit light curves to increase the signal to noise.

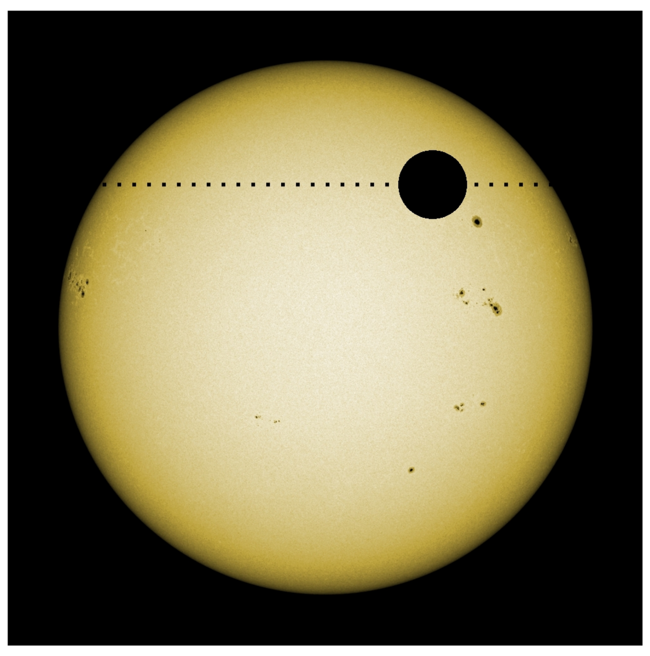
We detect the transit in X-rays at a confidence of 99.8% (if flaring observations are included: 98%). The data favor an **X-ray transit depth of 6-8%**, compared to an optical transit depth of only 2.4%.

We show a limb-brightened (coronal) best-fit transit model to the data (—); see Schlawin et al. (2010). We also show a limb-darkened (photospheric) best-fit model for comparison (- -).

We trace this back to a strongly extended planetary atmosphere, which is dense enough to be opaque to X-rays, but too thin to be visible at optival wavelengths:



Coronal X-ray transit



Photospheric optical transit

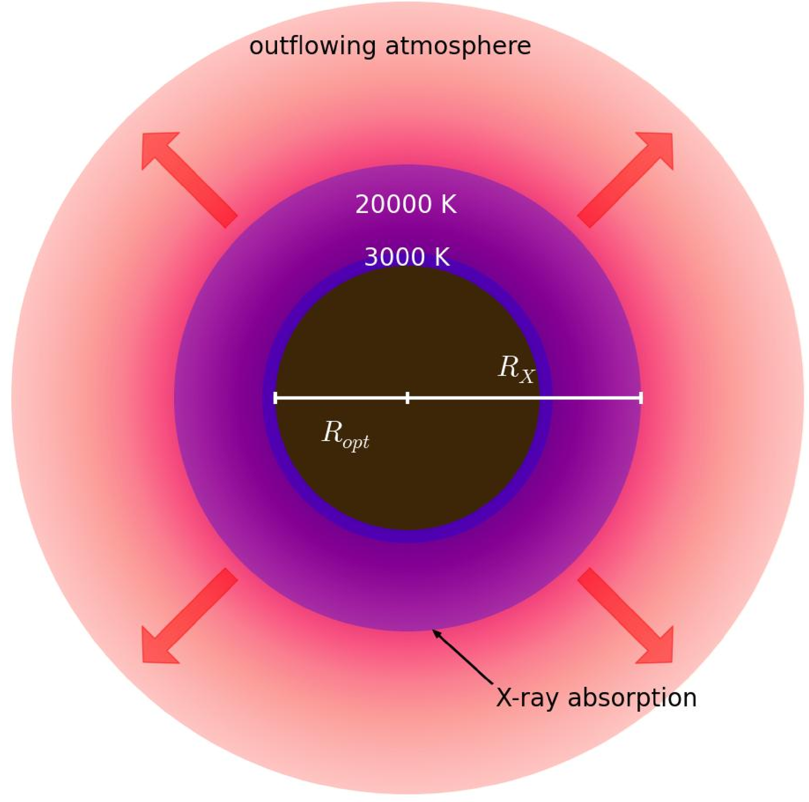
Implications for the atmosphere

Planetary atmosphere is X-ray opaque out to an altitude of ca. $1.75\,R_P$

Minimum required density: $1-10 \times 10^{10}\,\mathrm{cm}^{-3}$, depending on atmospheric metallicity

Required upper atmosphere temperature: $\approx 20,000\,\mathrm{K}$, in line with theoretical models

X-ray absorption not dependent on hydrogen ionization level (this is what constrains UV measurements in the Lyman-α line) $\longrightarrow$ X-rays will yield signal even if most of the hydrogen in the outer atmosphere is ionized



The fine print

Stellar coronae are inhomogeneous and intrinsically time-variable, so there's a few things we have to be careful about:

- Is the X-ray transit so deep because the planet crosses one X-ray bright active region multiple times?
  No, the stellar rotation period is ca. 12 days, while the observations are mostly spaced 2-5 days apart, so it can't be the same active region.
- Is there an activity belt on the star, so that the planet always crosses an untypically X-ray bright part of the stellar corona?
  No. We checked optical transit observations where starspots were detected; the transit path is not more spotted than the rest of the star.
- Could several coronal regions have conspired to lead to a spurious deep X-ray transit?
  Unlikely, but we can't completely rule it out with the data we have now. That's why we have applied for additional X-ray observations.

Literature

- The exoplanetary X-ray transit:
  K. Poppenhaeger, J.H.M.M. Schmitt, S.J. Wolk, "Transit observations of the Hot Jupiter HD 189733b at X-ray wavelengths", accepted by ApJ (2013), arXiv:1306.2311
- Limb-brightened transit models:
  E. Schlawin et al., "Exoplanetary Transits of Limb-brightened Lines: Tentative Si IV Absorption by HD 209458", ApJL 722, 1, L75 (2010)
- Transits of HD 189733b at UV wavelengths:
  see for example V. Bourrier et al., "Atmospheric escape from HD 189733b observed in H I Lyman-α: detailed analysis of HST/STIS September 2011 observations", A&A 551, id.A63 (2013)