天关卫星时代的恒星 X 射线耀发研讨会

恒星XUV辐射与行星大气流体逃逸

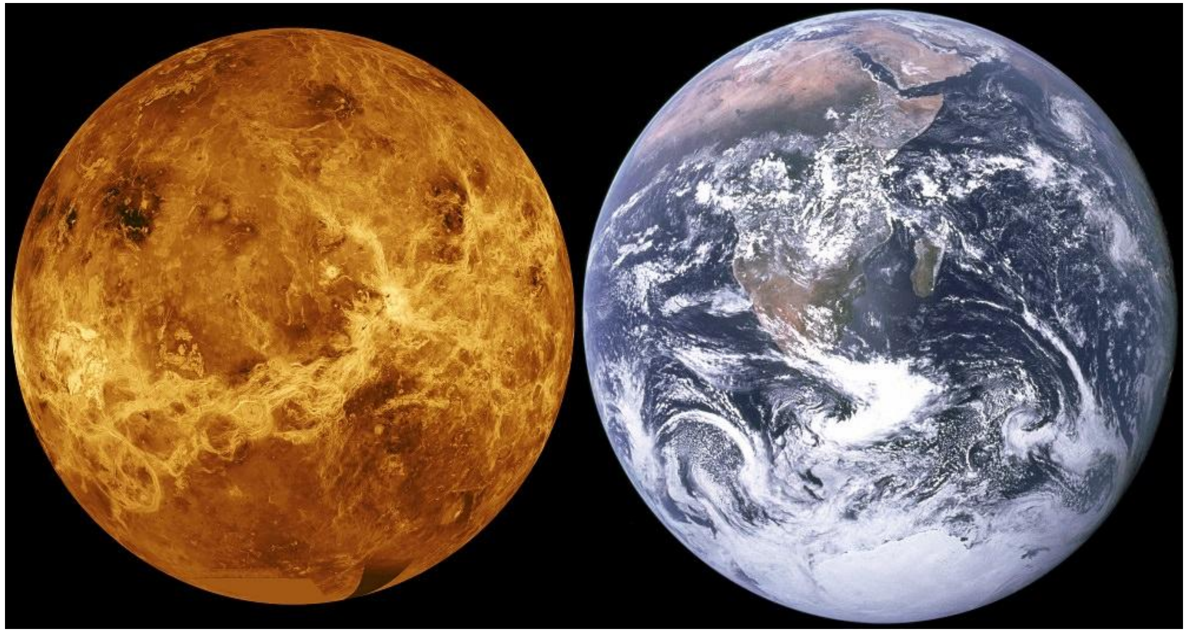
中国科学院云南天文台 恒星物理研究团组

郭建恒 闫冬冬等

2025-5-28 北京

背景介绍

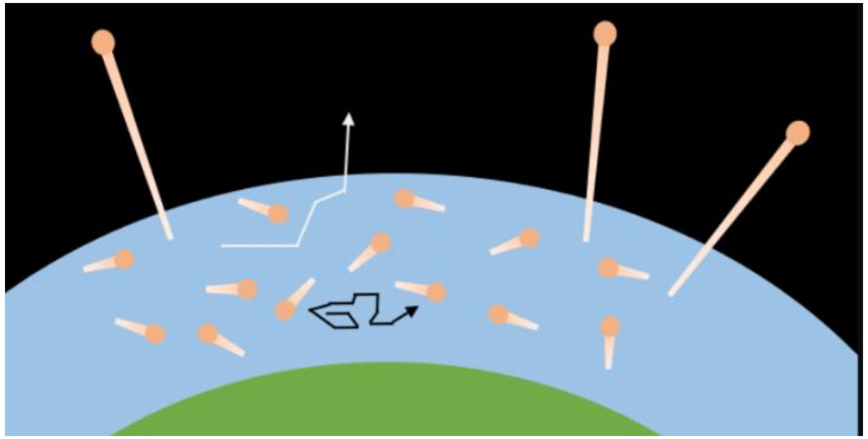
行星的宜居性

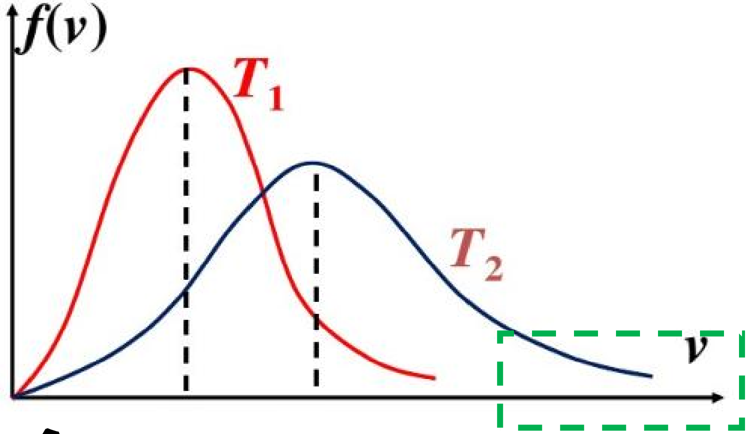


地球的过去、现在和未来?

行星大气的物质在逃逸！

早在1924年，Jeans就提出行星系统存在持续的损失物质！





Jeans 逃逸

热速度>逃逸速度

逃逸率：

$$\Phi(escape) = N_i \left(\frac{v_{thermal}}{2\sqrt{\pi}}\right)(1+\lambda_{ex})e^{-\lambda_{ex}}$$

Jeans parameter $\lambda = \frac{GM_p\mu}{R_p\kappa T} = \frac{\Delta U\ \mu}{\kappa T}$

太阳系行星有各种大气逃逸过程

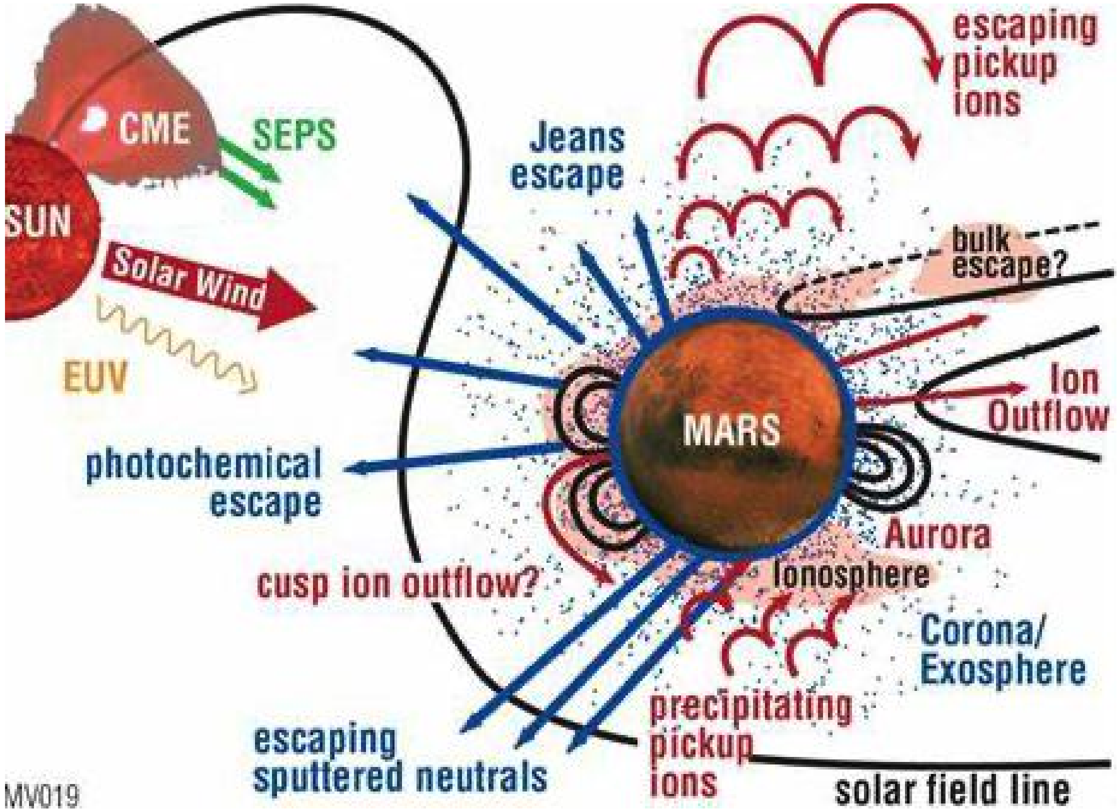
缺乏大气流体逃逸！

Table 1
Average escape rates from Venus' upper atmosphere involving hydrogen and oxygen

Planet	Venus	Mars
Escape process	Loss rate (s^{-1})	Loss rate (s^{-1})
Jeans: H	2.5×10^{19}	1.5×10^{26}
Photo-chemical reactions: H*	3.8×10^{25}	
Photo-chemical reactions: O*		2.8×10^{24}
Electric field force[a]: H^+	$\leqslant 7 \times 10^{25}$	
Ion pick up: H^+	1×10^{25}	1.2×10^{25}
Ion pick up: H_2^+	$<10^{23}$	1.2×10^{25}
Pick up: O^+	1.6×10^{25}	3×10^{24}
Detached plasma clouds: O^+	$5 \times 10^{24} - 1 \times 10^{25}$	$\approx 1 \times 10^{24}$
Sputtering: O	6×10^{24}	2.2×10^{23}

The thermal, photo-chemical and ion loss rates are based on our model results. The sputtered O loss rates is taken from Luhmann and Kozyra (1991) and the electric force driven H^+ loss rates due to ionospheric holes on Venus nightside are based on estimations of Hartle and Grebowsky (1993).

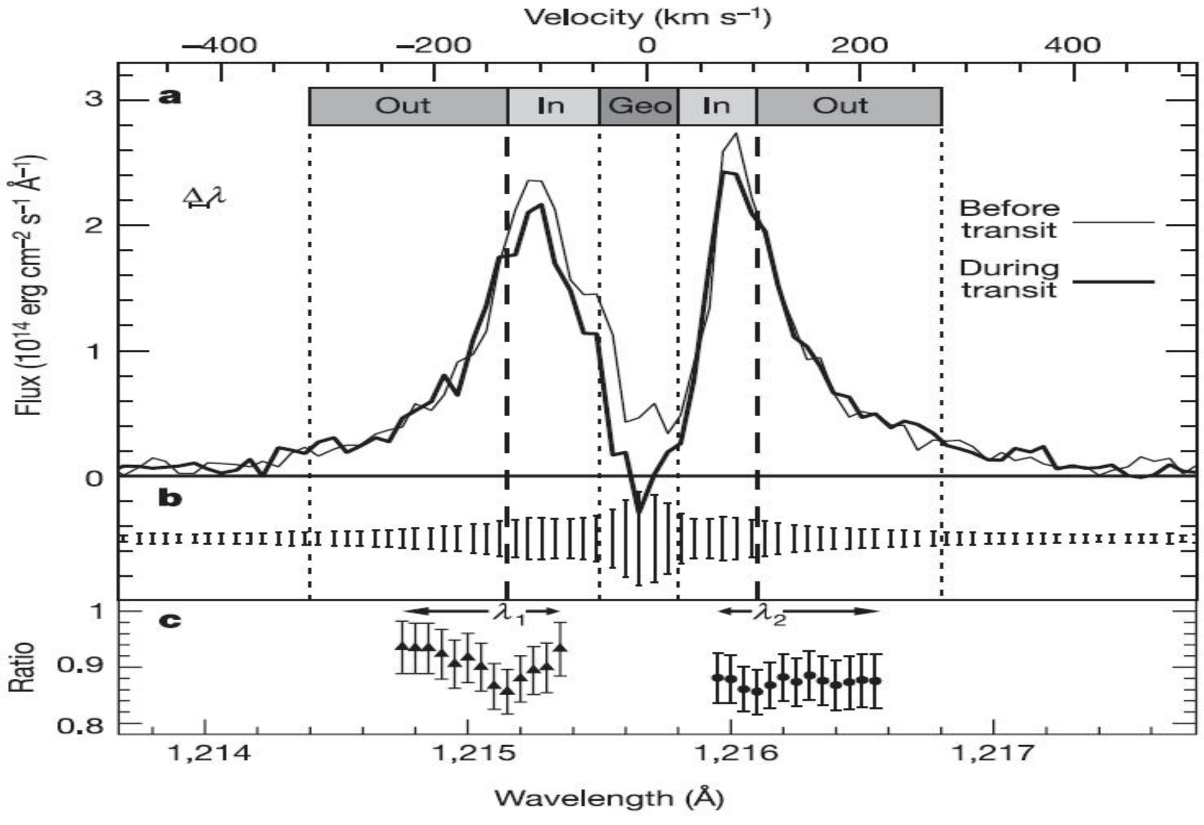
[a]Estimated by Hartle and Grebowsky (1993).



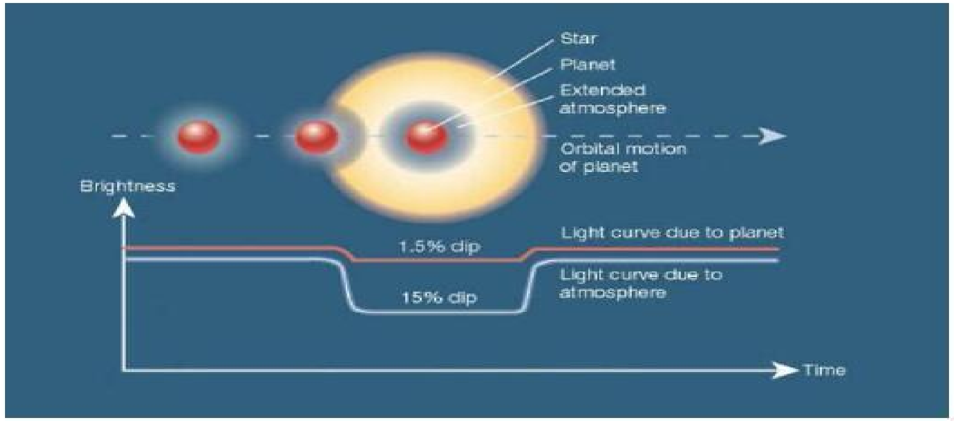
Lammers + 2005

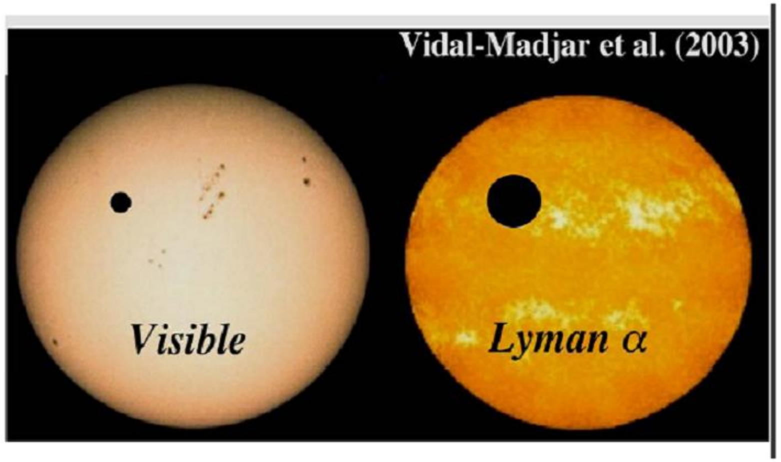
系外行星大气流体逃逸的观测发现

HD 209458b-Lyα

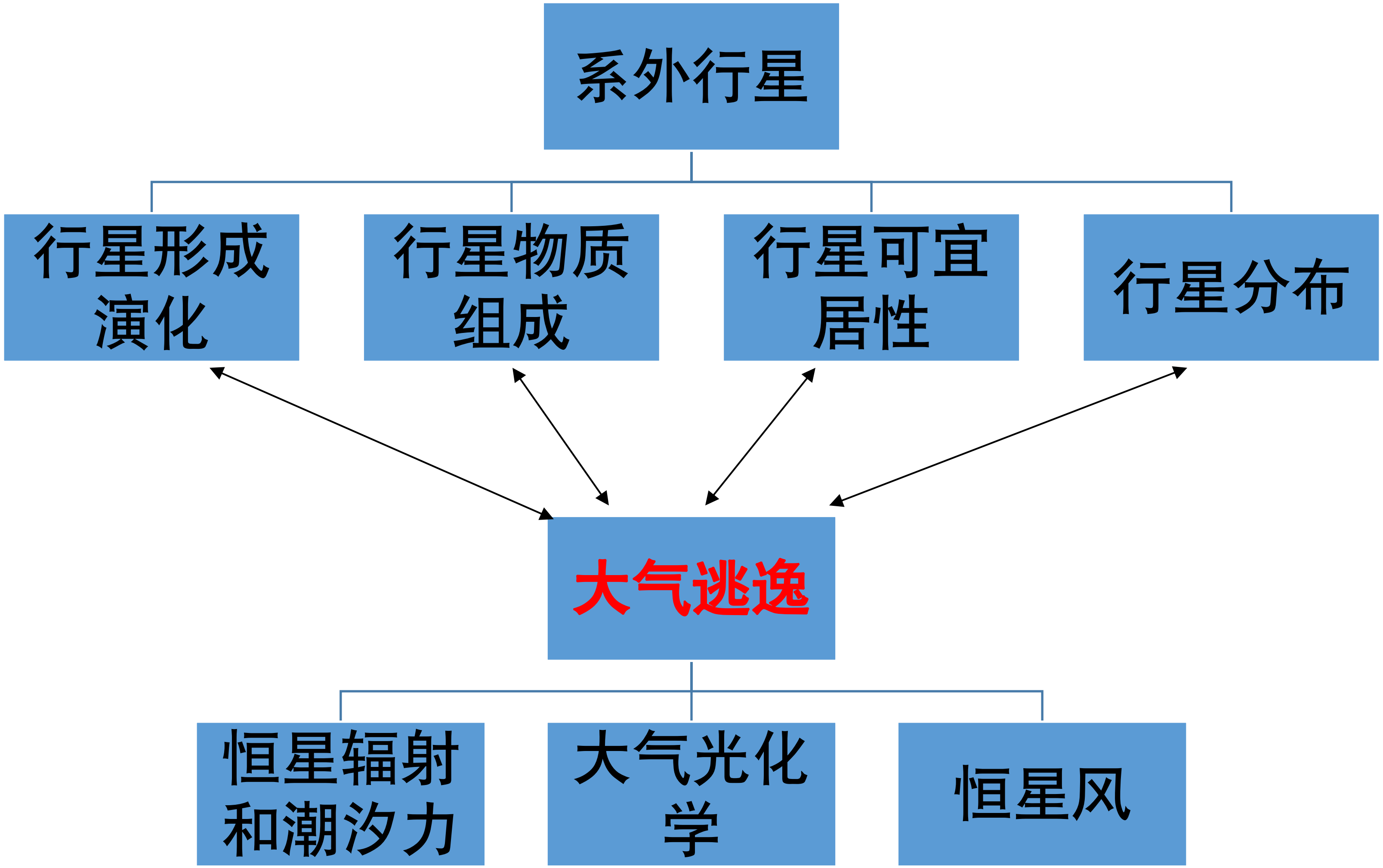


Vidal-Madjar et al. (2003)





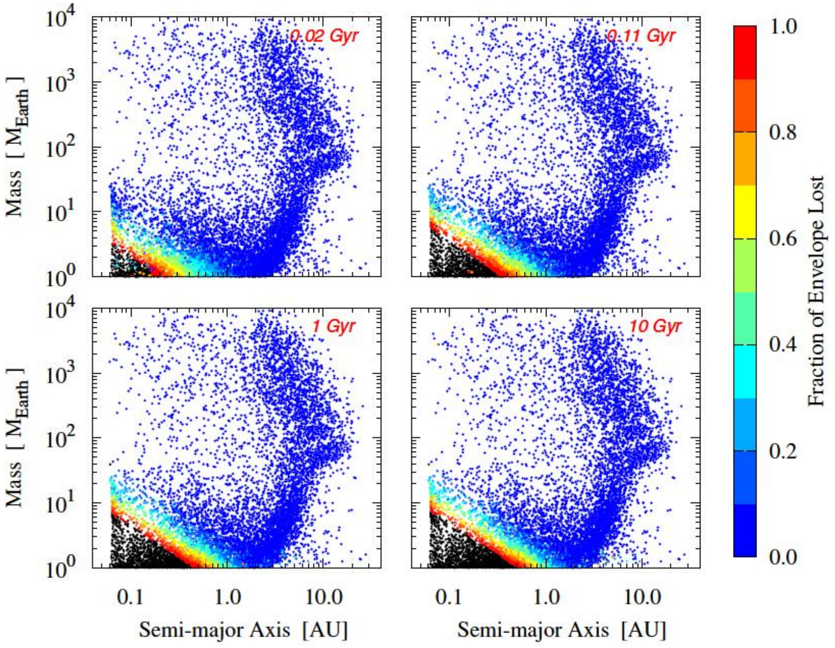
系外行星大气流体逃逸是链接系外行星各领域的纽带

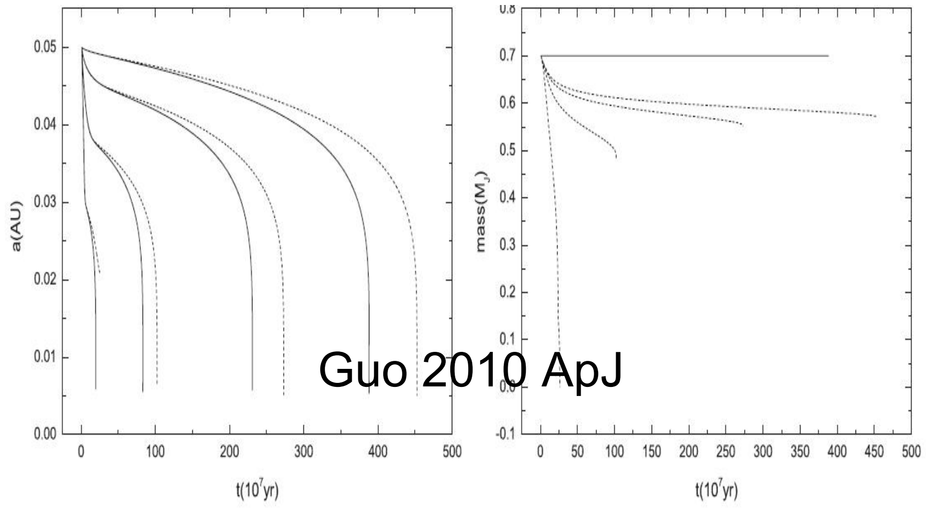


精确预言系外行星大气的物质损失率、化学组成等对上述问题有极大的帮助。

流体大气逃逸造就了行星族群

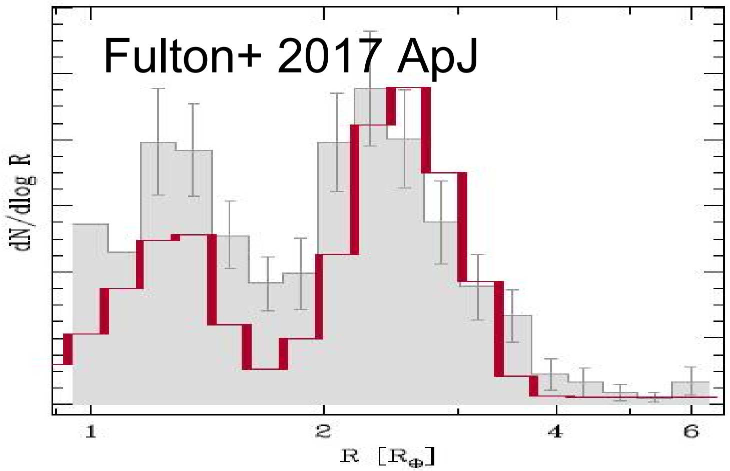
Jin+ 2014 ApJ



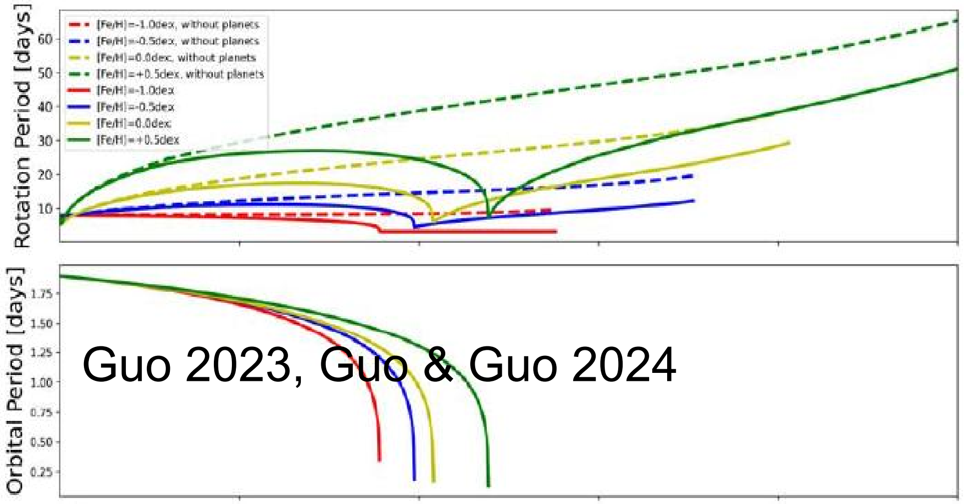


Guo 2010 ApJ

轨道演化



Fulton+ 2017 ApJ

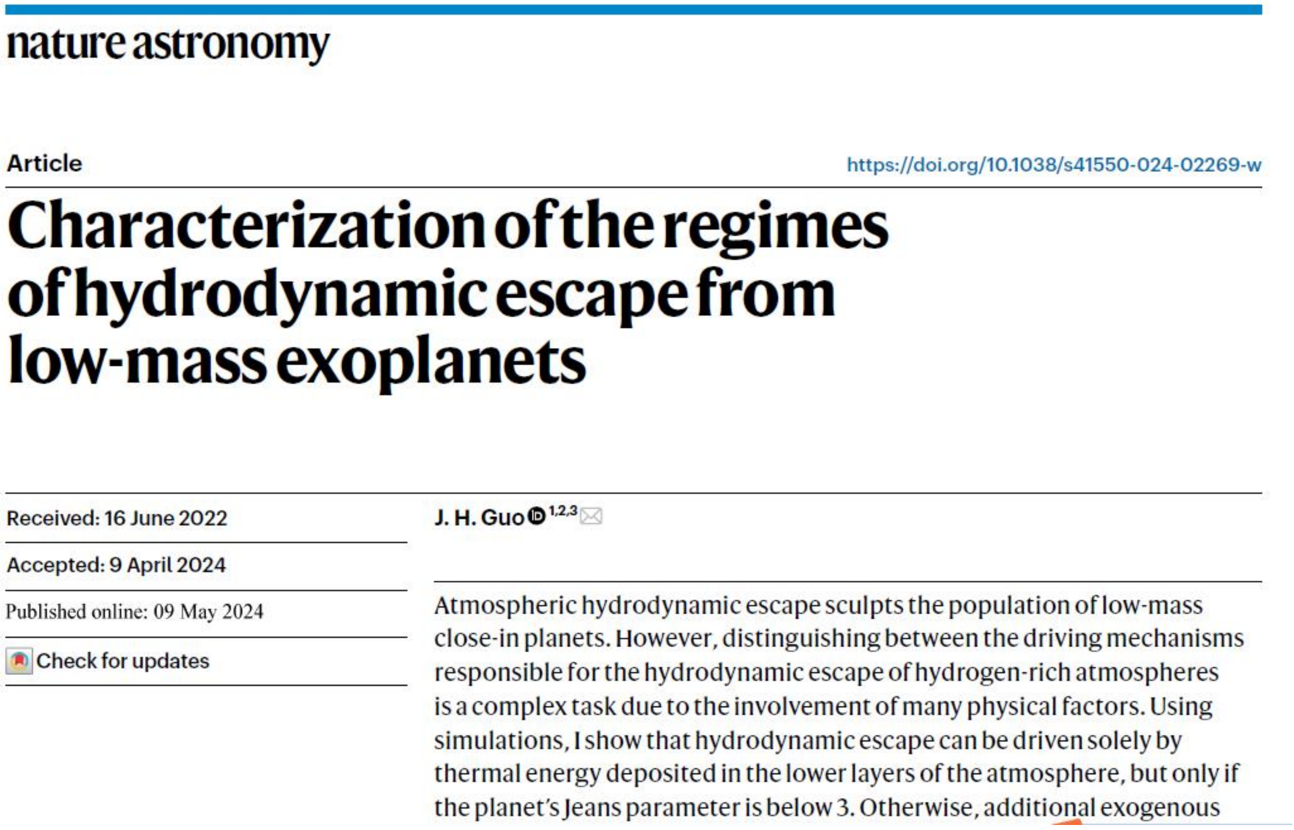


Guo 2023, Guo & Guo 2024

潮汐演化

大气逃逸的驱动机制

➢ 使用改进的金斯参数对低质量行星的流体大气逃逸做出了分类（Guo, 2024, Nature Astro.)



nature astronomy

Article https://doi.org/10.1038/s41550-024-02269-w

Characterization of the regimes of hydrodynamic escape from low-mass exoplanets

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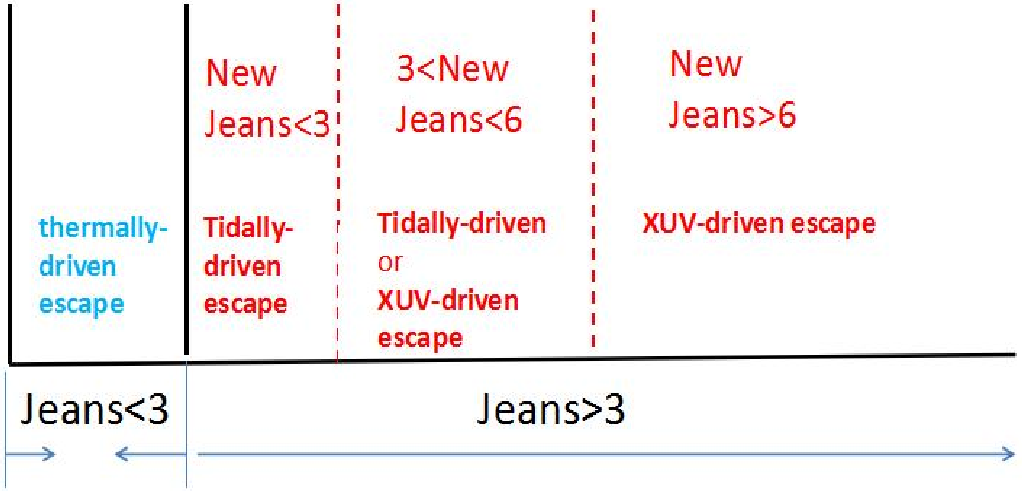
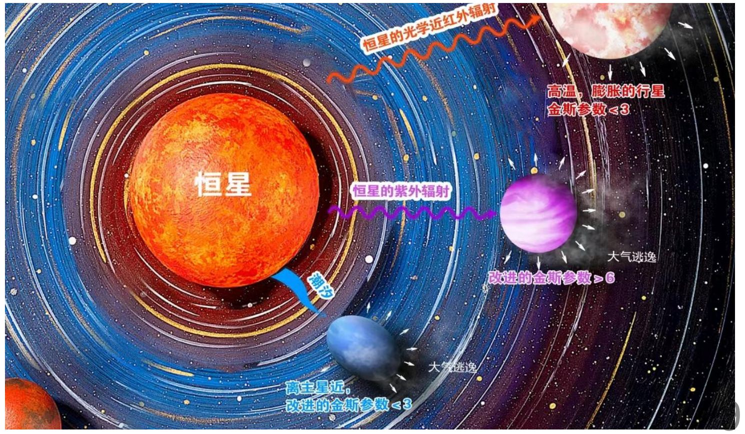
Check for updates

J. H. Guo[1,2,3]

Atmospheric hydrodynamic escape sculpts the population of low-mass close-in planets. However, distinguishing between the driving mechanisms responsible for the hydrodynamic escape of hydrogen-rich atmospheres is a complex task due to the involvement of many physical factors. Using simulations, I show that hydrodynamic escape can be driven solely by thermal energy deposited in the lower layers of the atmosphere, but only if the planet's Jeans parameter is below 3. Otherwise, additional exogenous





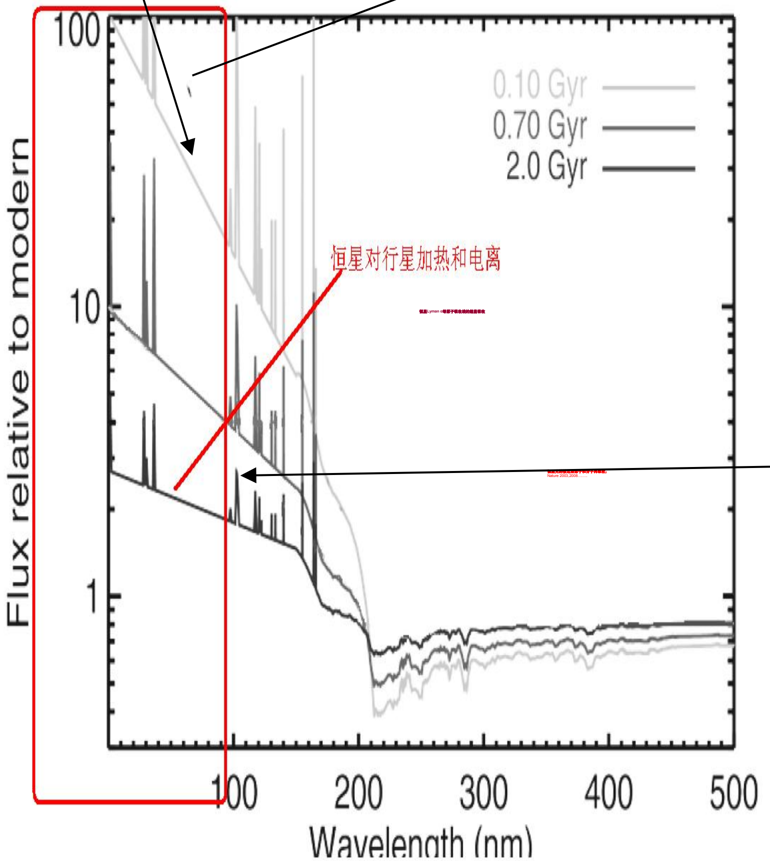
恒星XUV辐射与透射谱信号

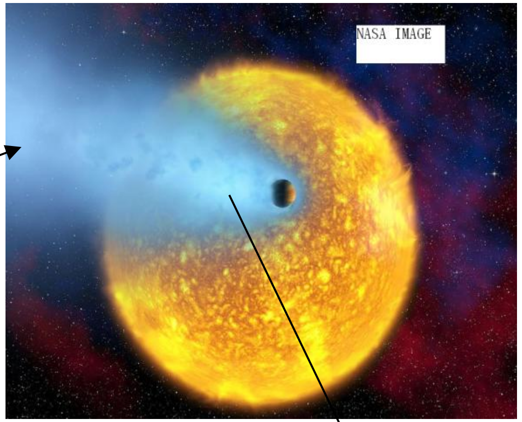
为什么恒星的XUV重要

恒星XUV影响行星大气的化学组成、逃逸率、观测信号以及可宜居性！

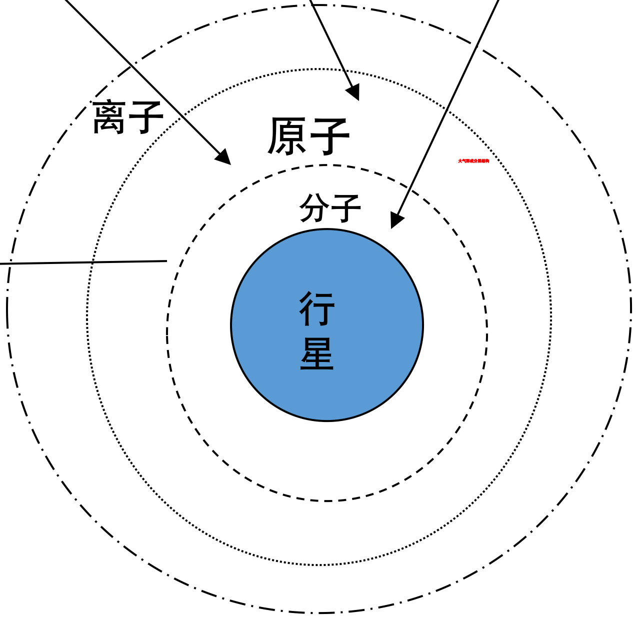
但是，我们对主星X-ray知道的不多，对EUV知道的很少！

恒星X-Ray & UV辐射驱动的行星大气逃逸

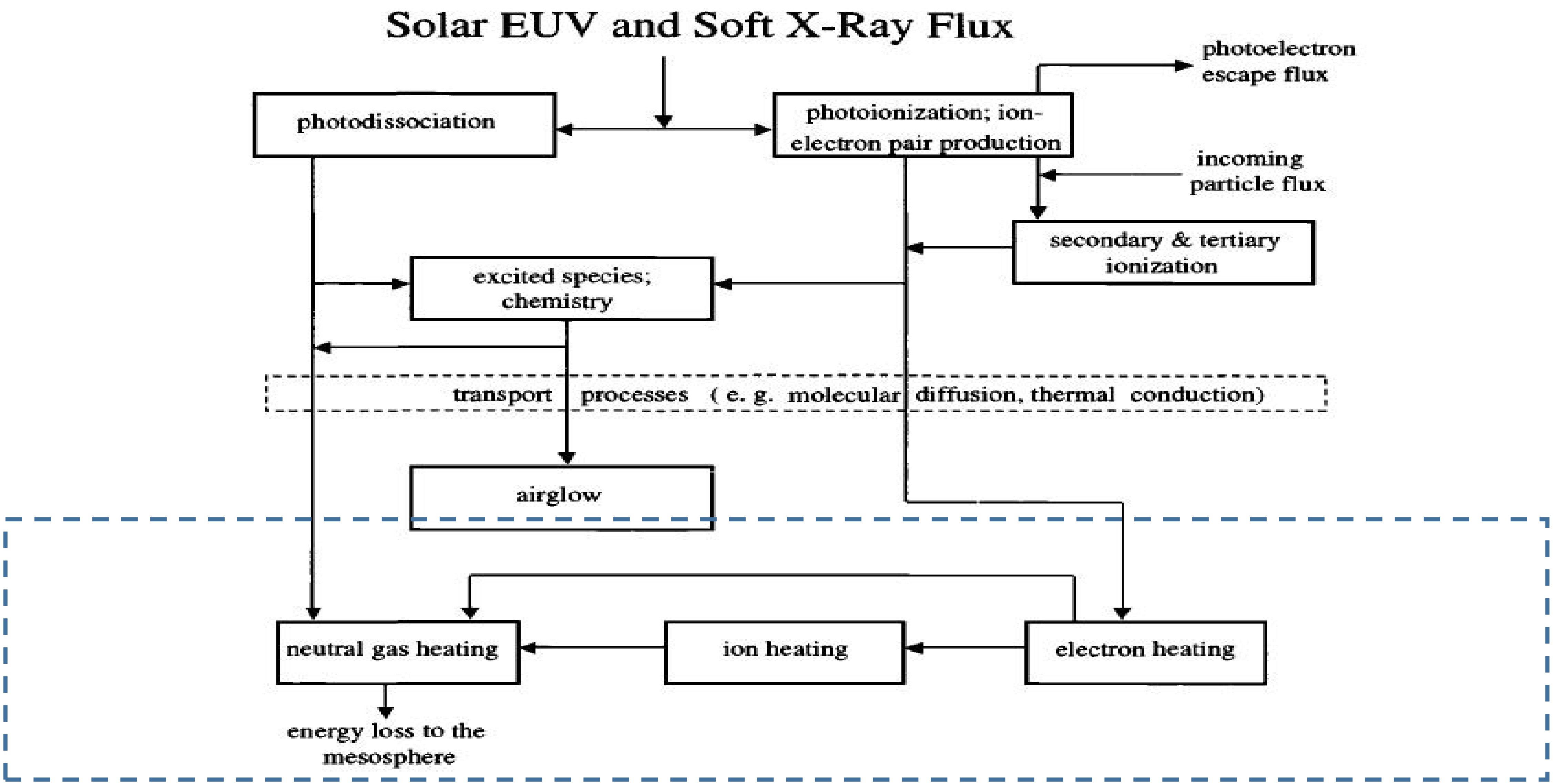




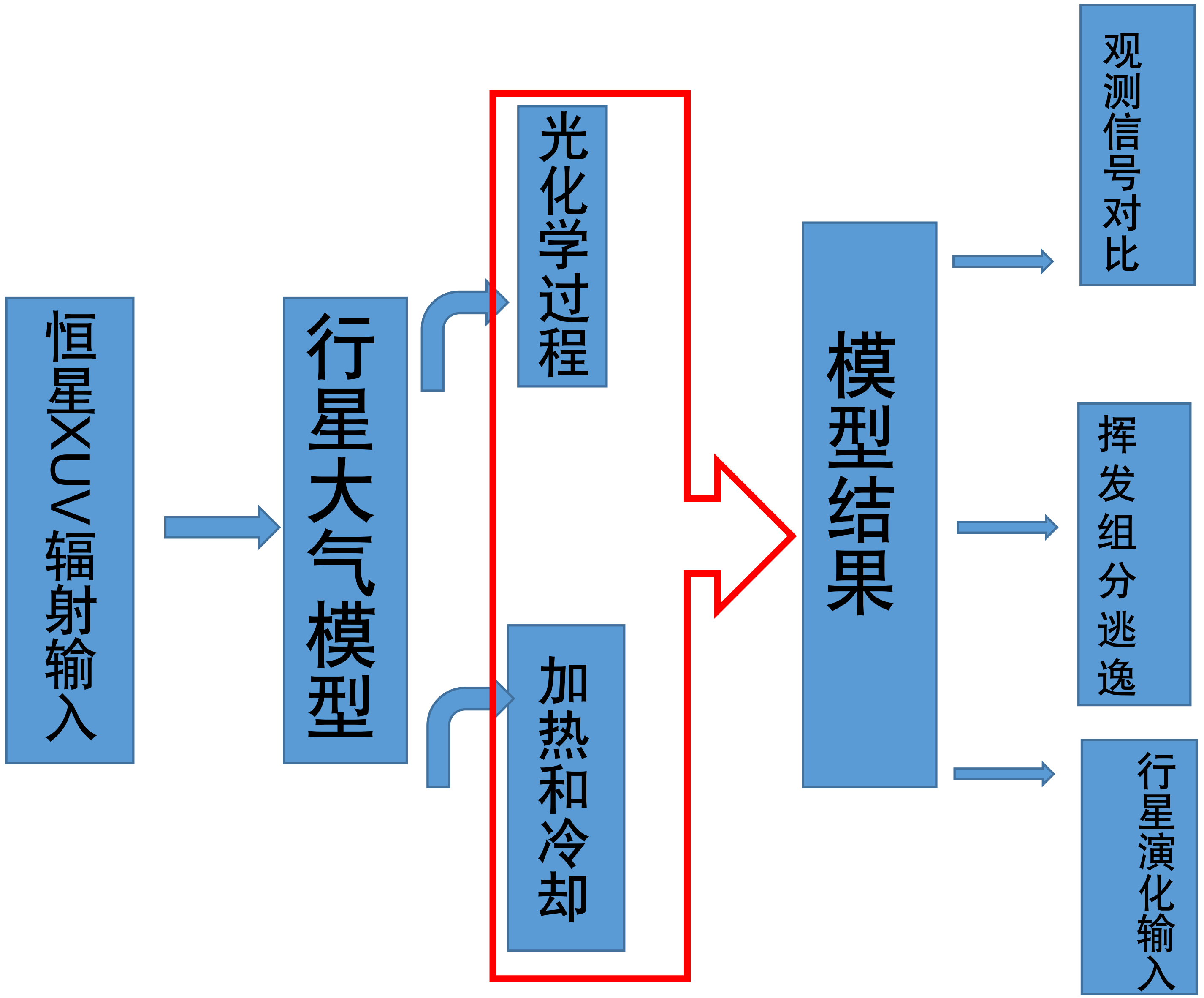
底层大气结构的探测



XUV光化学过程：能量吸收、元素的产生和消失

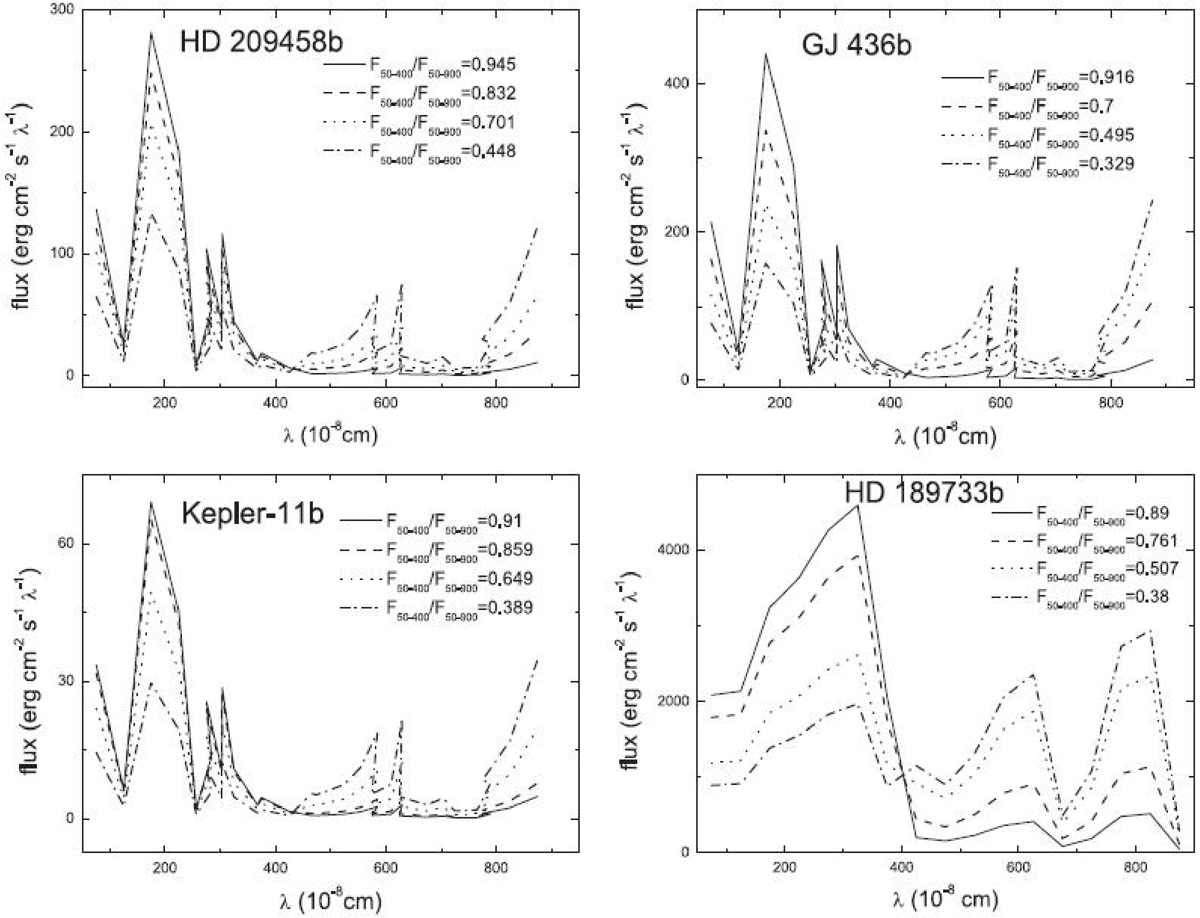


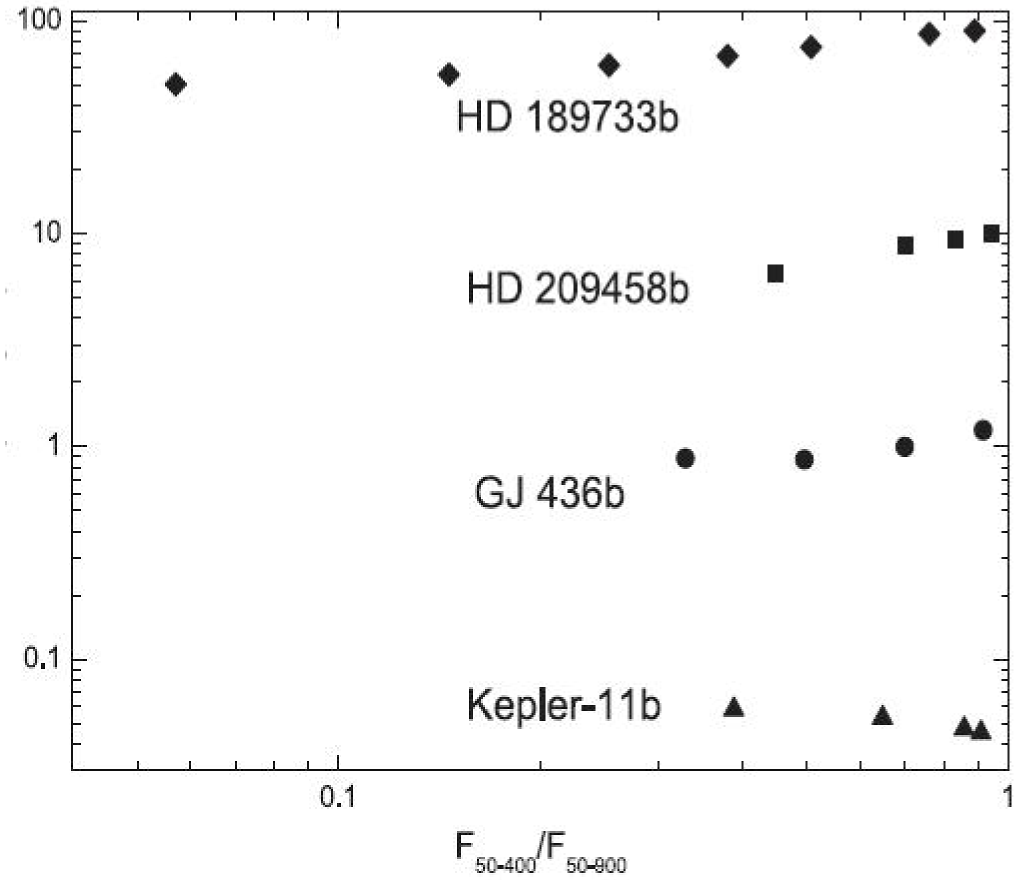
恒星XUV辐射驱动的大气逃逸



恒星XUV辐射的影响：物质损失率~50%的改变

$$\mathrm{Heat} = \sum_s n_s \sum_\lambda \eta_{\lambda,s} F_\lambda e^{-\tau_\lambda} \sigma_{\lambda,s},$$

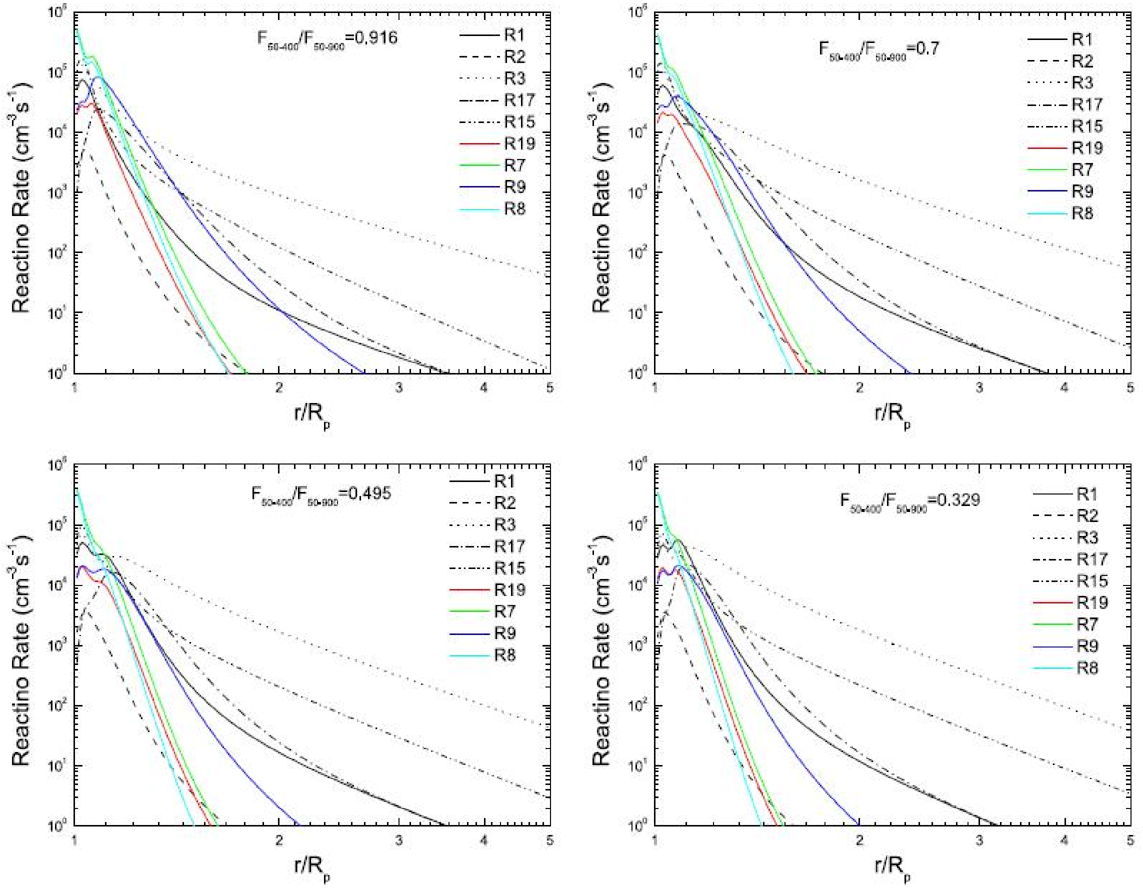




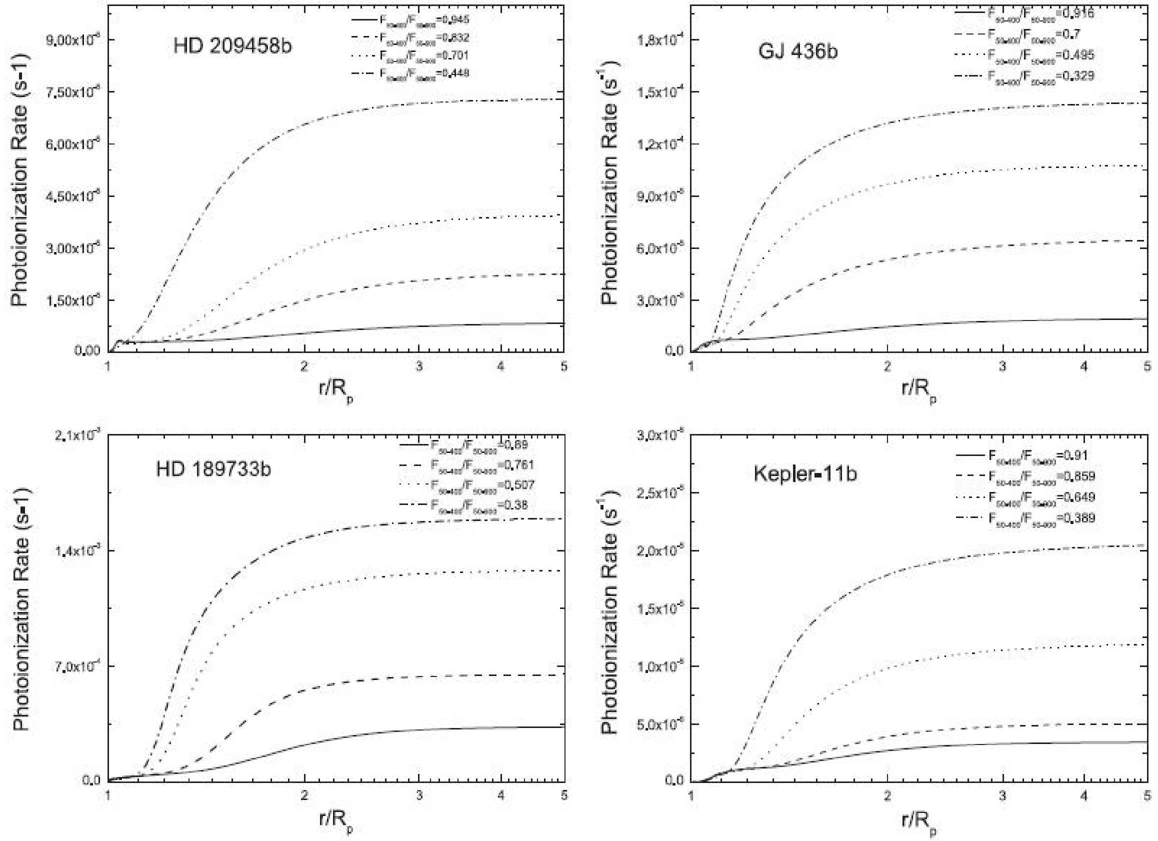
Guo & Ben-Jaffel 2016，ApJ

恒星XUV辐射的影响：对化学的改变

XUV对化学反应

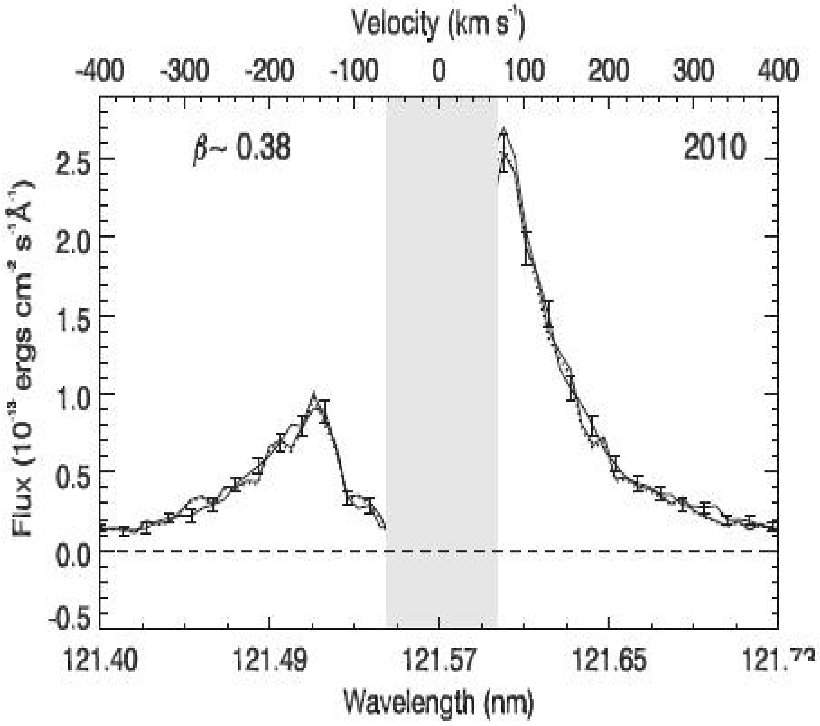


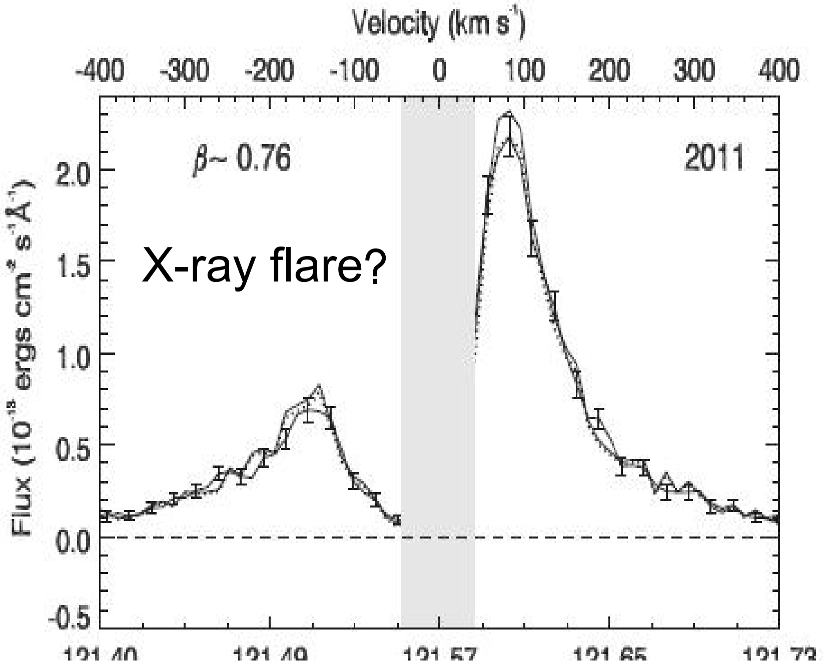
光致电离率（H）$\propto\sigma_\nu\propto\nu^{-3}$



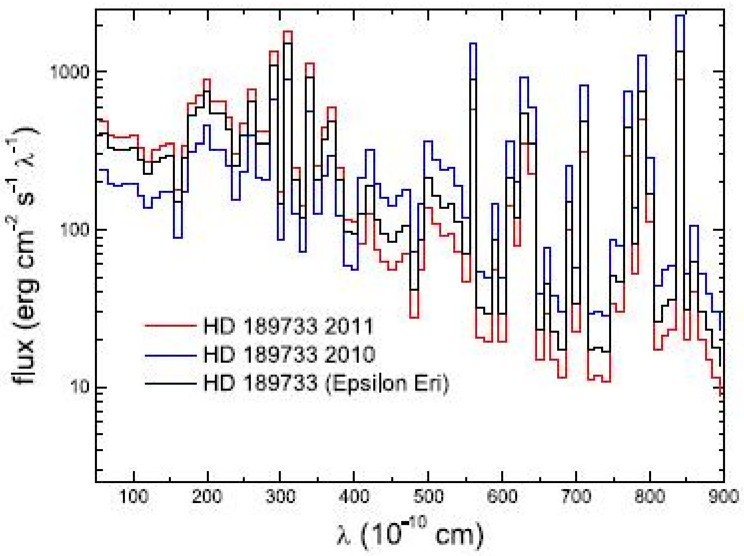
Guo & Ben-Jaffel 2016，ApJ

HD 189733b -Lya 时变

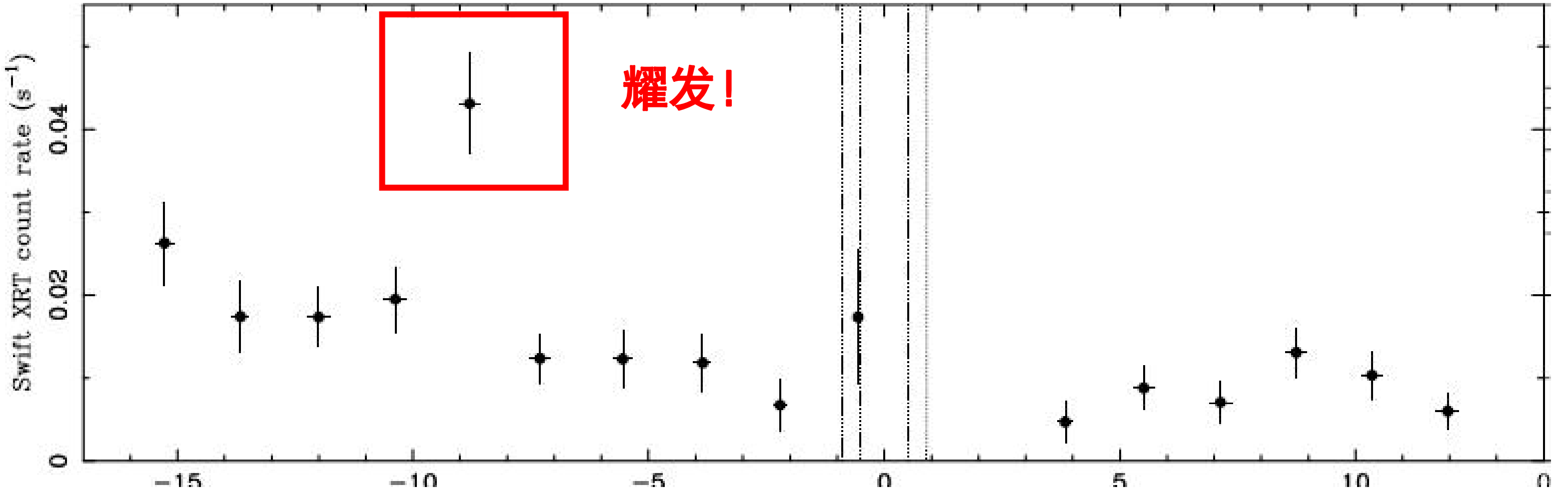




HD189733 XUV的重构



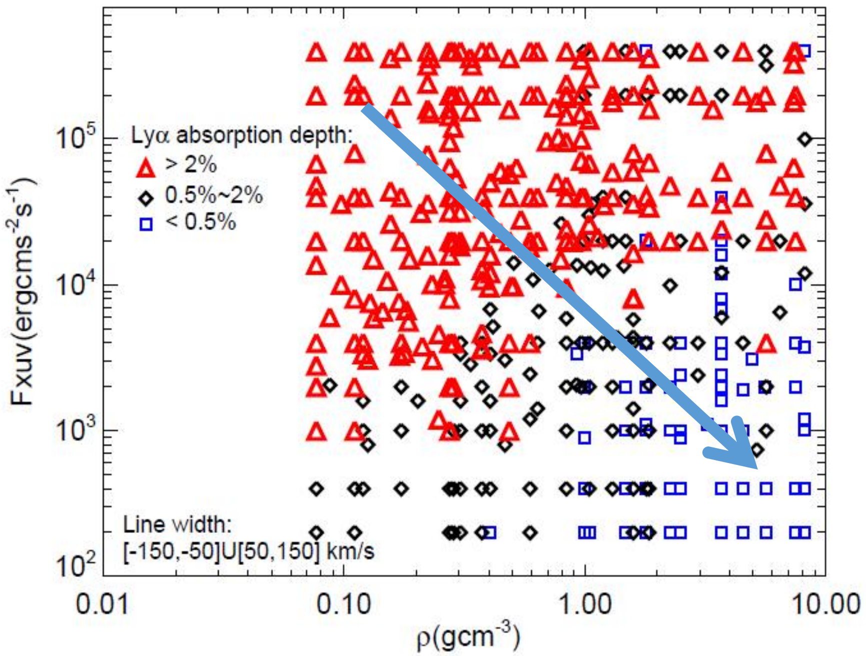
$\beta = F(1\text{-}400)/F(1\text{-}912)$



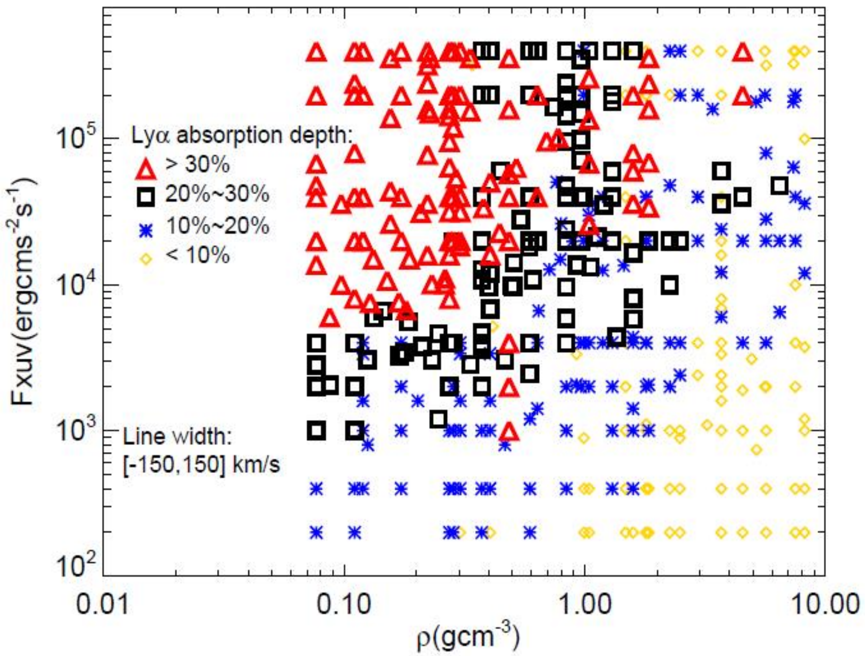
Guo & Ben-Jaffel 2016，ApJ

恒星 Lyα 被行星逃逸大气吸收

Close-in giant planets



Line width: [-150,-50]U[50, 150] km/s

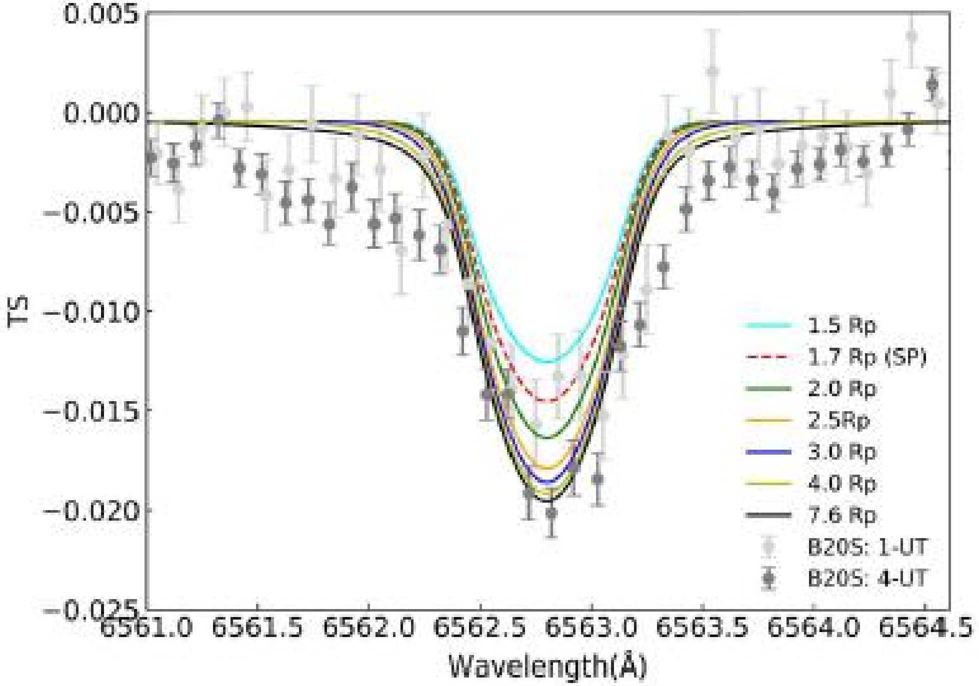


Line width: [-150, 150] km/s

Yan & Guo 2019 ApJ

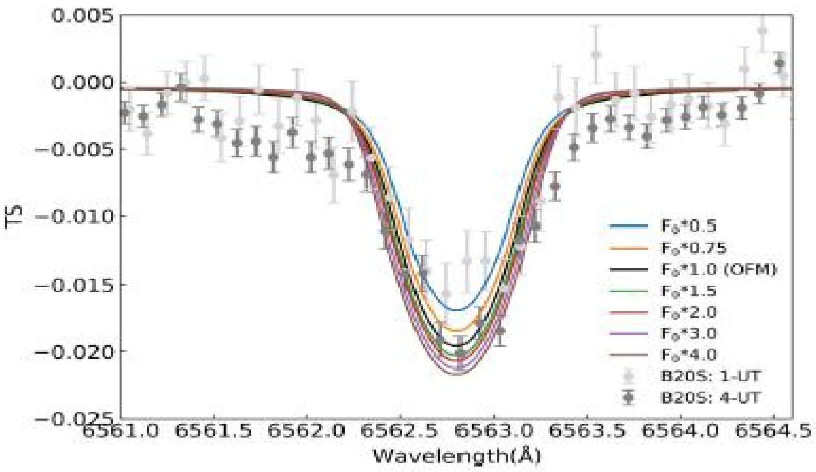
首次证明大气逃逸可以在光学波段有可观测的信号

WASP-121b

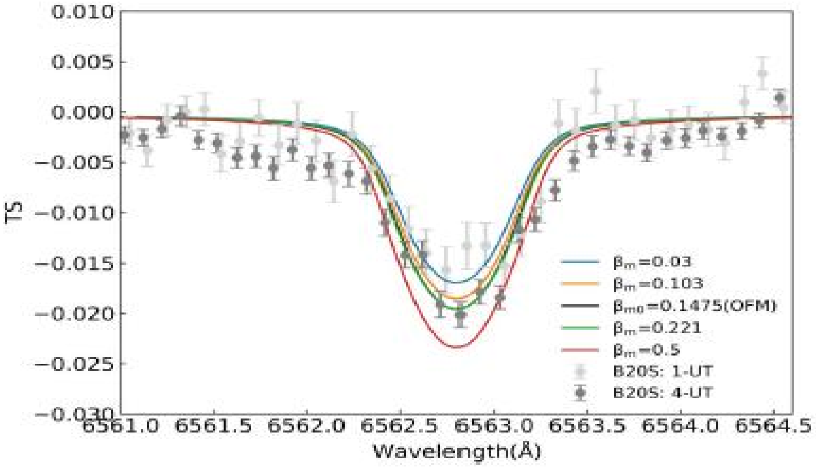


Yan,Guo & Huang + 2021 ApJL

XUV Profile依然不确定

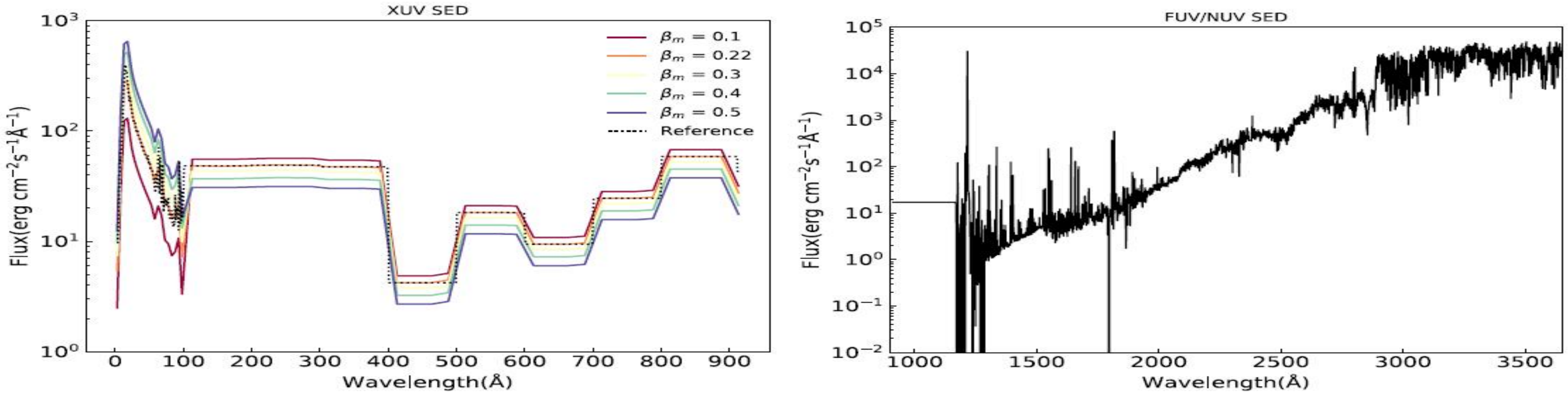


(a)



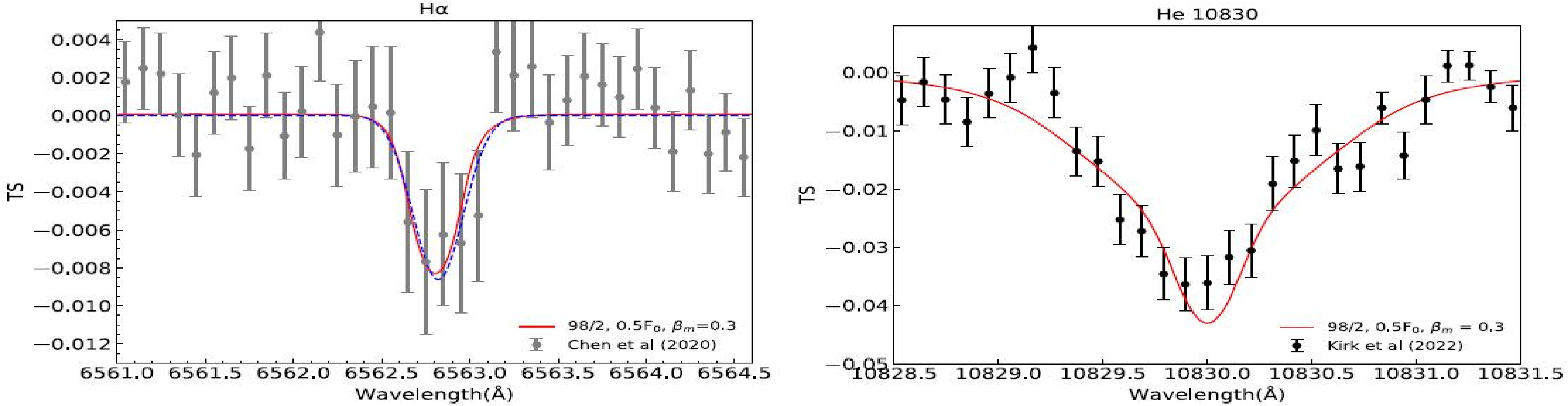
第一次对WASP-52b Hα和He10830的同时解释

(MUSCLES treasure survey：EPS-Eri，K2)

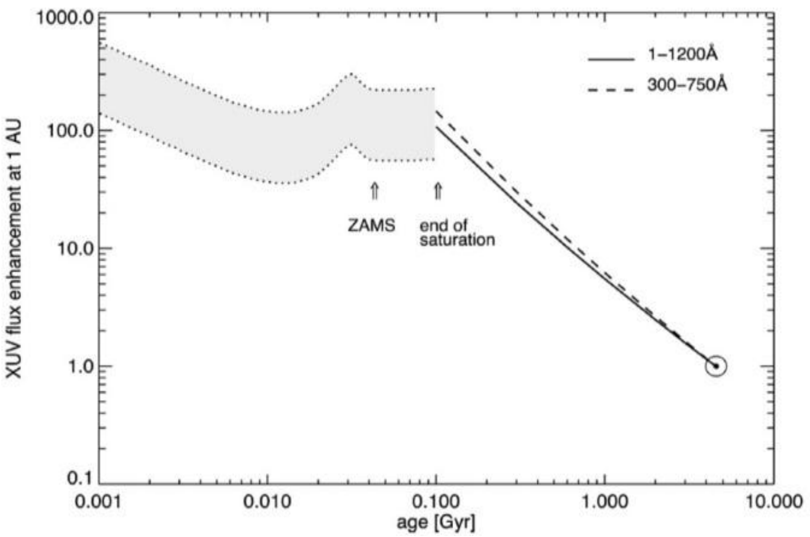


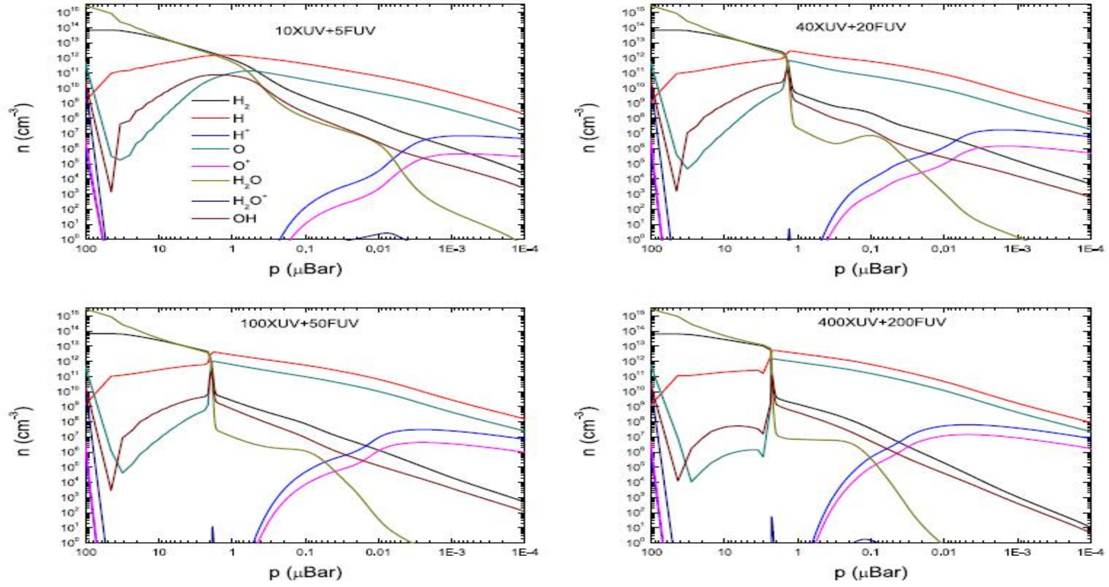
(a)

(b)



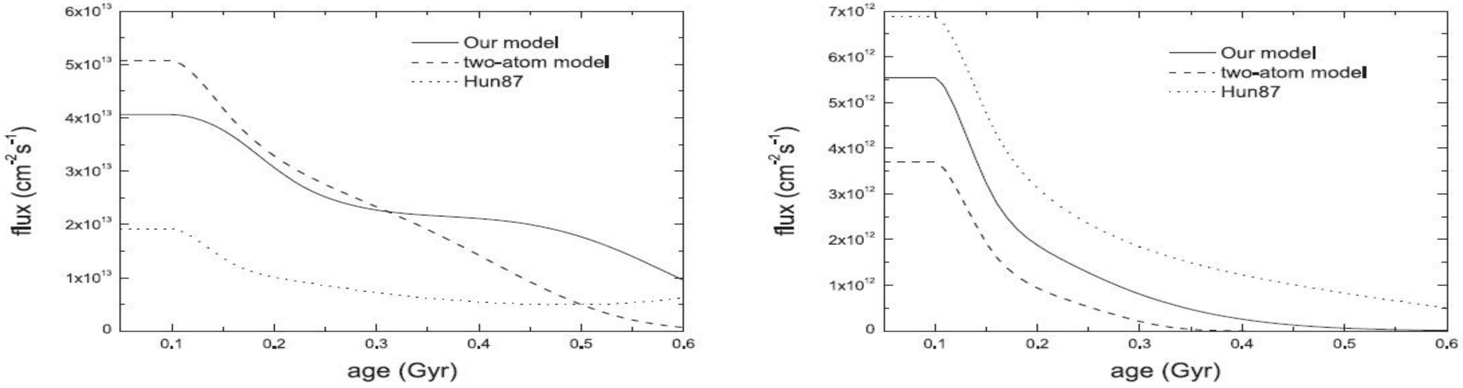
恒星XUV长期演化与行星宜居性





H2O的光化学产物

类地行星在诞生的几亿年内可以丢失几个地球海洋的水



Guo 2019, ApJ

部分电离大气中不同质量粒子逃逸的质量分馏（fractionation）

恒星冕的不均匀性、耀发.....？

大气中所有组分可以等比例的离开行星吗？

重元素可以扩散到多高？

单流模型危机：HD 209458b和WASP-52b低氦高层大气

Lampon+ 2020, 2021;Yan+ 2022

A&A 636, A13 (2020)
https://doi.org/10.1051/0004-6361/201937175

Astronomy & Astrophysics

Modelling the He I triplet absorption at 10 830 Å in the atmosphere of HD 209458 b

M. Lampón[1], M. López-Puertas[1], L. M. Lara[1], A. Sánchez-López[1], M. Salz[2], S. Czesla[2], J. Sanz-Forcada[3], K. Molaverdikhani[4], F. J. Alonso-Floriano[5], L. Nortmann[6,7], J. A. Caballero[3], F. F. Bauer[1], E. Pallé[6,7], D. Montes[8], A. Quirrenbach[9], E. Nagel[2], I. Ribas[10,11], A. Reiners[12], and P. J. Amado[1]

The Astrophysical Journal, 936:177 (38pp), 2022 September 10
https://doi.org/10.3847/1538-4357/ac8793

Modeling the Hα and He 10830 Transmission Spectrum of WASP-52b

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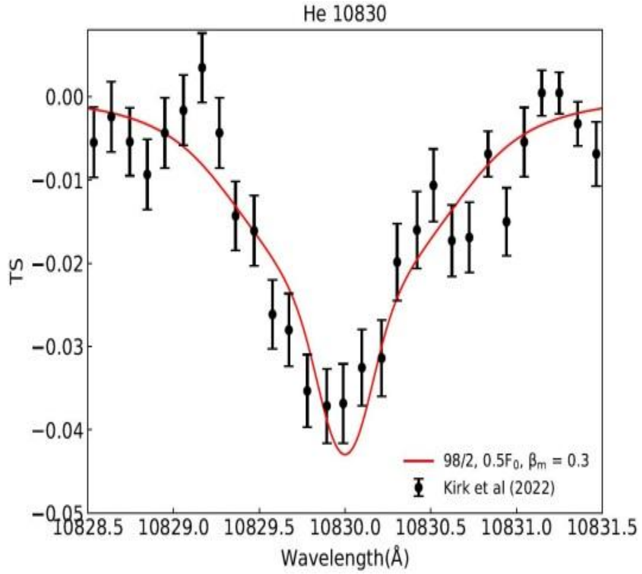
[4] Korea Astronomy and Space Science Institute, 776 Daedeokdae-ro, Yuseong-gu, Daejeon 34055, Republic of Korea
[5] Astronomy and Space Science Major, University of Science and Technology, 217, Gajeong-ro, Yuseong-gu, Daejeon 34113, Republic of Korea
[6] Key Laboratory of Planetary Sciences, Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing 210023, People's Republic of China
Received 2022 May 16; revised 2022 July 26; accepted 2022 August 6; published 2022 September 13

H/He ratio:98/2

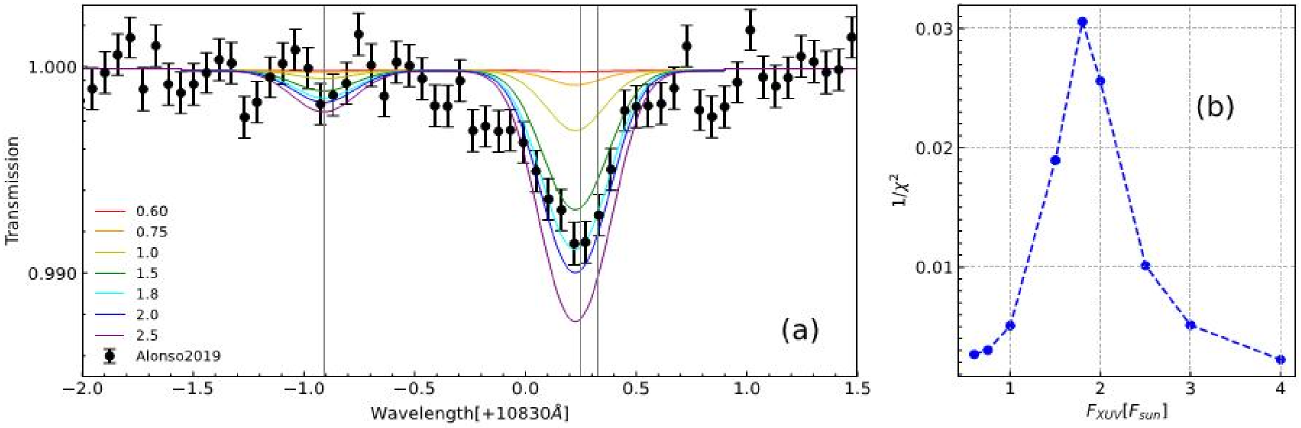
Results. We find that the measured spectrum constra
Hydrogen is almost fully ionised at altitudes above 2.9
at effective radii from 1.16 to 1.30 R_P, and that the He I
averaged mean molecular weight is confined to the 0.
than 90/10, and most likely approximately 98/2. We al



质量分馏是HD 209458b低氦丰度的原因？

研究背景：目前对行星大气中He10830信号的拟合表明大气中的氢氦比远高于太阳值，其原因尚不清楚。

结果和意义：只有下边界一半的氦可以逃逸，造成在上层大气氦的占比减少。自洽地限定了行星大气中氢氦比。

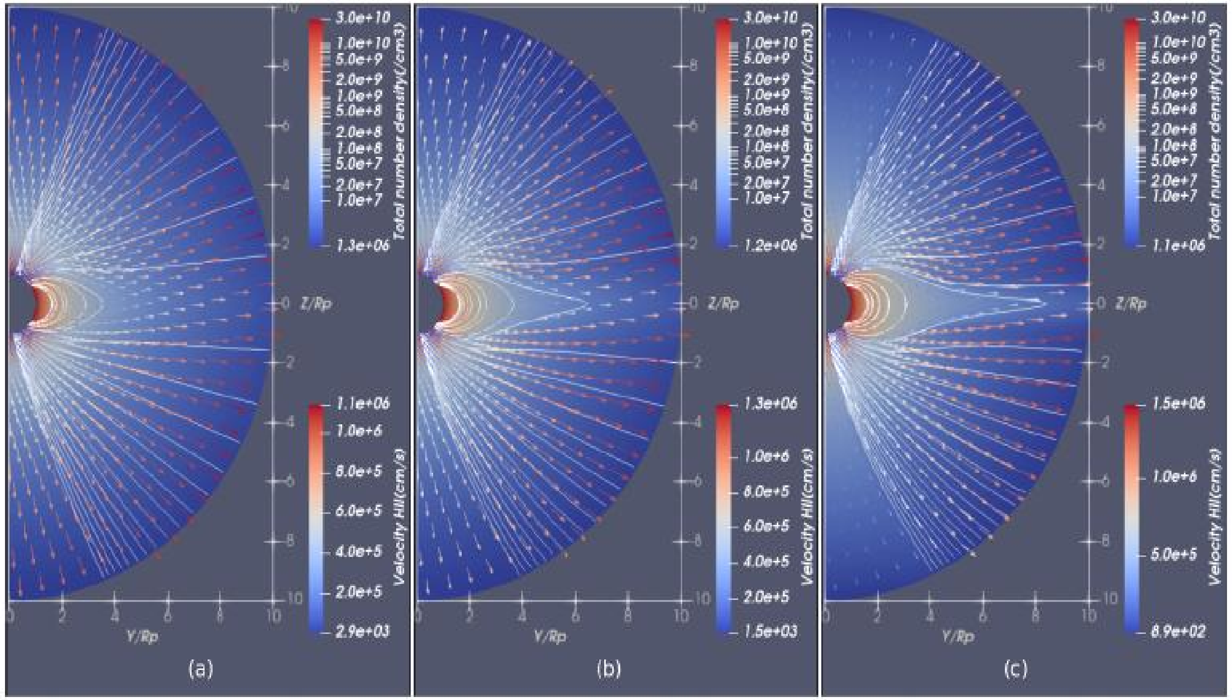


Xing, Yan & Guo 2023,ApJ

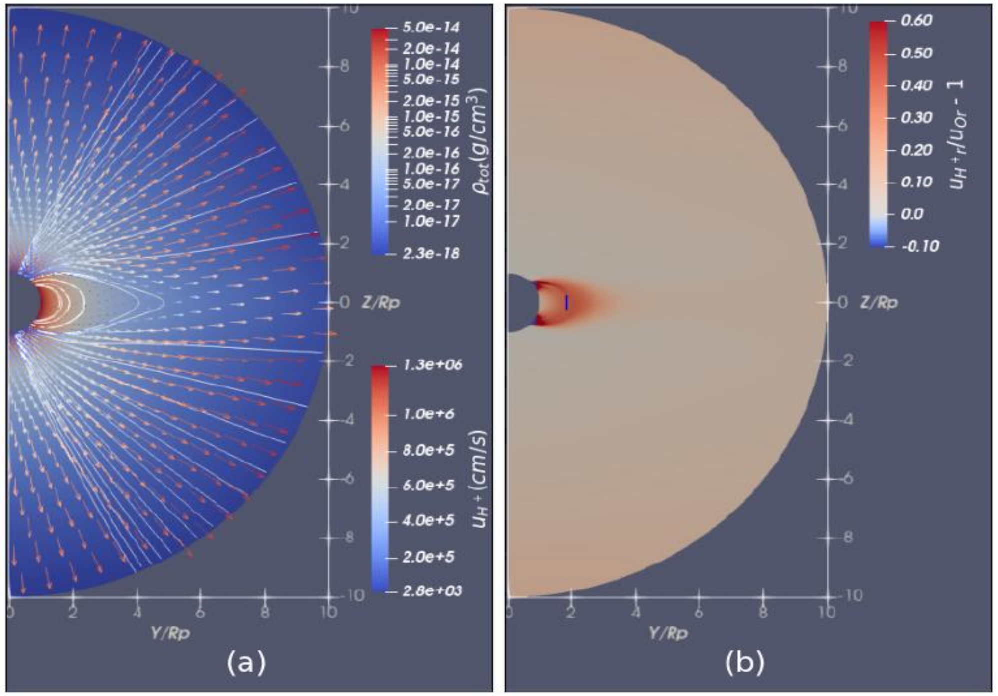
有磁场的情景

Xing, Yan & Guo 2024，RAA

H&H^+：B=1G-2G-3G



H^+&O：B=1G



磁场-带电粒子-中性粒子的相互平衡构造了有磁场下的大气逃逸模式，中性组分质量越大分馏越严重，氢离子和氧原子的速度可以相差50%

X-ray探测行星高层大气、超巨星风的成团性

EP&其他X-ray望远镜

The Astronomical Journal, 168:177 (11pp), 2024 October https://doi.org/10.3847/1538-3881/ad6d6

Detecting Exoplanet Transits with the Next Generation of X-Ray Telescopes

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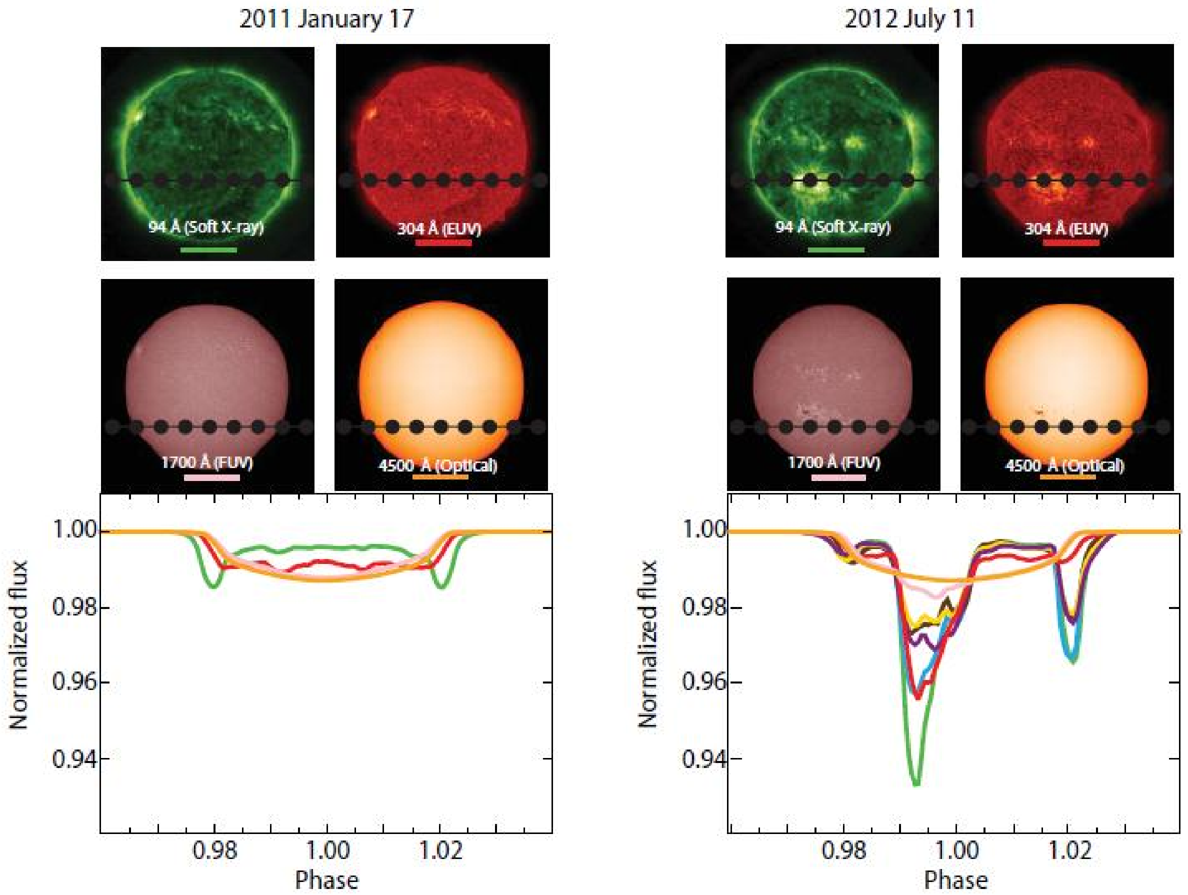
Abstract

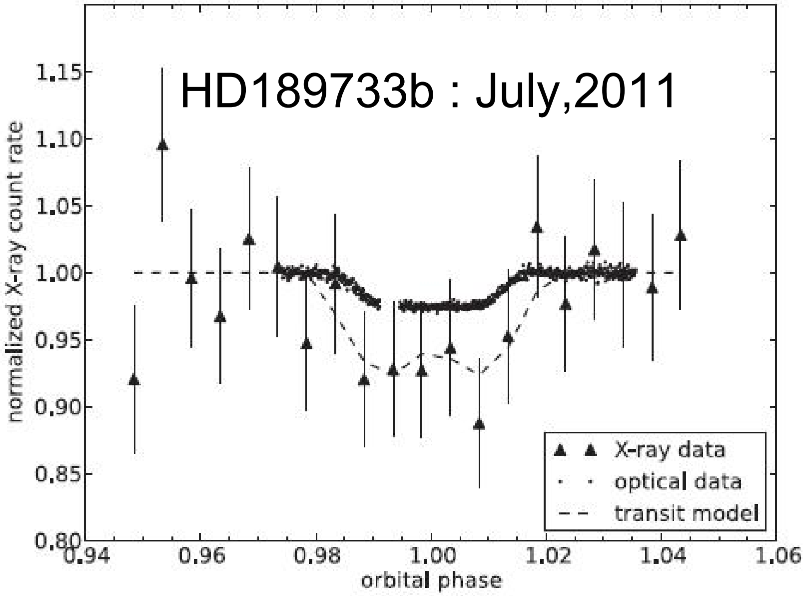
Detecting exoplanet transits at X-ray wavelengths would provide a window into the effects of high-energy irradiation on the upper atmospheres of planets. However, stars are relatively dim in the X-ray, making exoplanet transit detections difficult with current X-ray telescopes. To date, only one exoplanet (HD 189733 b) has an X-ray transit detection. In this study, we investigate the capability of future X-ray observatories to detect more exoplanet transits, focusing on both the NewAthena Wide Field Imager instrument and the proposed Advanced X-ray Imaging Satellite (AXIS), which provide more light-collecting power than current instruments. We examined all the transiting exoplanet systems in the NASA Exoplanet Archive and gathered X-ray flux measurements or estimates for each host star. We then predicted the stellar count rates for both AXIS and NewAthena and simulated light curves, using null-hypothesis testing to identify the top 15 transiting planets ranked by potential detection significance. We also evaluate transit detection probabilities when the apparent X-ray radius is enlarged due to atmospheric escape, finding that ⩾five of these planetary systems may be detectable on the $>4\sigma$ level in this scenario. Finally, we note that the assumed host star coronal temperature, which affects the shape of an X-ray transit, can also significantly affect our ability to detect the planet.

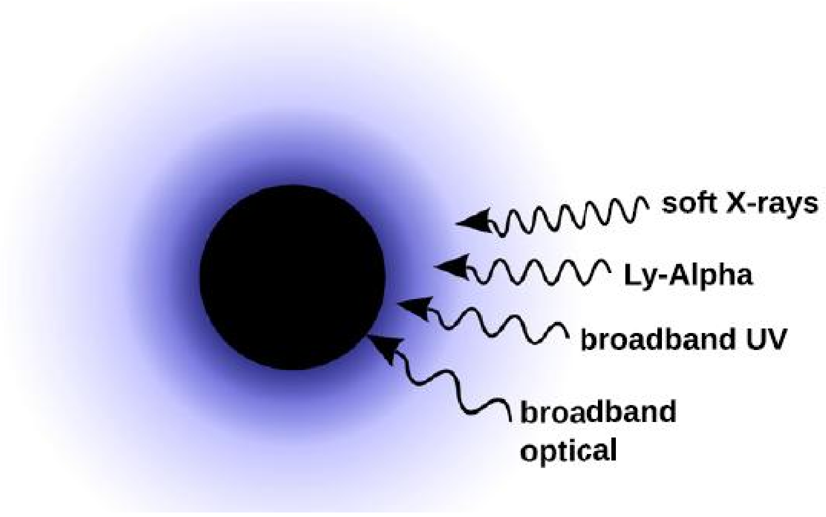
separate from super-Earths, believed to be rocky cores (J. E. Owen & Y. Wu 2017). Direct observation of escaping atmospheres provides the strongest means by which to test these hypotheses.

Observing transits in the X-ray provides another unique way to observe atmospheric escape. The first and only planetary transit to be detected in the X-ray is that of HD 189733 b (K. Poppenhaeger et al. 2013; P. J. Wheatley et al. 2024, in preparation), one of the earliest discovered planets and a canonical hot Jupiter. The results of K. Poppenhaeger et al. (2013) imply that the apparent radius of the planet is 50%–80% larger in the X-ray than it is in the optical. This can be attributed to an extended envelope of near-neutral material, for which X-ray absorption via the photoelectric effect is much stronger than typical absorption features in the UV, optical, and infrared—with the exception of Lyα. However, the utility of the Lyα feature is made difficult by absorption by the intervening interstellar medium. Additionally, interpreting the physical extent and mass-loss rates of planetary outflows from metal line and metastable He absorption is complicated by our lack of knowledge of the exact atmospheric conditions and (variable) radiation field that populates the relevant atomic states (A. Oklopčić 2019; L. Wang & F. Dai 2021). X-rays interact with inner-shell electrons, making the photoelectric absorption cross sections across a broad energy range relatively insensitive to the exact ion population. Thus, X-ray transits provide a more agnostic tracer of the physical extent of planetary atmospheres with which to measure atmospheric escape rates, making exoplanet transits a unique subject of interest for future X-ray observatories.

在X-ray的凌星探测有望对大气逃逸物理化学过程的理解带来更多的限制







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TRANSIT OBSERVATIONS OF THE HOT JUPITER HD 189733b AT X-RAY WAVELENGTHS

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X-ray in stellar physics

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Astronomy & Astrophysics

- Early-type stars(OB stars)
- Late-type stars(G-M stars)

X-ray temperatures and their radial distributions from winds of O-type supergiants: the effects of clumps

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- X-ray binary
- Young stars (pre-main sequence stars and proplanetary disk)

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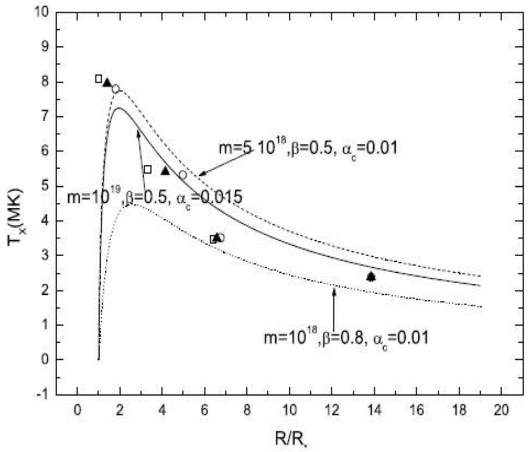
Table 1. Line widths of the program stars.

	Ion	Theoretical	Observational
ζ Ori A	O VII	610–880	500^a , 900 ± 200^b
	Ne IX	610–880	1360^a , 900 ± 200^b
	Mg XI	480–800	900 ± 200^b
	Si XIII	360–700	900 ± 200^b
ζ Pup	O VII	900–1100	
	Ne IX	780–1050	
	Mg XI	690–990	
	Si XIII	350–700	

Notes. [(a)] Cohen et al. (2006); [(b)] Waldron & Cassinelli (2000); [(c)] Kahn et al. (2001).



Early-type supergiants

TABLE 2

X-RAY DATA OF OBSERVED STARS

(0.2-4.5) keV

Name (1)	Effective Exposure Time (s) (2)	Net Intensity (cts s^{-1}) (3)	F_x (10^{-13} ergs cm^{-2} s^{-1}) (4)	L_x^o (10^{31} ergs s^{-1}) (5)	L_x (10^{31} ergs s^{-1}) (6)
9 Sgr	3906	0.057±0.005	11 ±1	35 ±3	58 ±5
ζ Pup	2529	0.57 ±0.02	114 ±4	25 ±0.9	26 ±1
λ Cep	1827	0.033±0.006	6.5±1.1	7.8 ±1.4	16 ±3
HD 152248	1551	0.037±0.007	7.4±1.4	32 ±6	65 ±12
HD 151804	9698	0.011±0.002	2.1±0.3	8.2 ±1.2	13 ±2
29 CMa	1965	<0.014	<2.9	<12	<14
α Cam	1153	0.027±0.005	5.5±1.0	9.4 ±1.8	13 ±2
ε Ori	1541	0.32 ±0.02	64 ±3	14.8 ±0.7	20 ±1
κ Ori	1757	0.086±0.008	17 ±2	6.2 ±0.6	9 ±1
γ Ara	5705	0.020±0.003	4.0±0.5	2.3 ±0.3	2.7±0.4
ρ Leo	7228	<0.0073	<1.5	<1.6	<1.7
139 Tau	6654	<0.0063	<1.3	<2.2	<2.9
HD 190603	3231	<0.016	<3.3	<10	<28
χ^2 Ori	2734	<0.0047	<0.94	<2.2	<4.4
θ Ara	3013	0.0075 ±0.0022	1.5±0.4	0.98±0.3	1.2±0.4
55 Cyg..........	7711	<0.0039	<0.79	<1.1	<2.6
o^2 CMa	1770	<0.0074	<1.5	<1.8	<2.0
η CMa...........	6295	<0.0046	<0.92	<0.64	<0.7
67 Oph..........	7743	<0.0080	<1.6	<1.1	<1.7
μ Sgr	3138	<0.0091	<1.8	<5.5	<8.5
α Cyg	2879	<0.0056	<1.1	<0.48	<0.5

结论

恒星的**X-ray&UV**辐射决定了行星大气特性和可宜居性！