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The evaporation of planetary atmospheres

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Abstract. In recent years the focus of exoplanet research has shifted from the mere detection to detailed characterization. Precise measurements of the masses and radii of transiting planets have shown that some low-mass planets have extended atmospheres while others are bare rocks. Hybrid atmospheres consisting of a mixture of Hydrogen and large amount of heavy elements have also been detected. A key factor in explaining this diversity of planetary atmospheres is the erosion by the X-ray and EUV-radiation (XUV) from the host-star. The evaporation through XUV-radiation has already been measured for a few exoplanets.The apparent weakness of the Ca II HK and the Mg II h&k emission cores has been interpreted as evidence for the evaporation of planetary atmospheres. The interpretation is that the evaporating material from the planet forms a thick torus which absorbs the Ca II HK and the Mg II h&k lines from the host star. In this contribution a new way how to prove, or disprove this hypothesis by observations is proposed. It is furthermore shown that there are enough bright targets already known that can be observed, and more will be found with the PLATO mission.

Key words: planet – atmosphere – star – activity

1. The evolution of the atmospheres of low-mass planets

Before exoplanets were discovered, it was generally thought that they would resemble the planets in our solar system, but research in the past years have shown that exoplanets are much more diverse. Precise measurements of the masses and radii of transiting planets allowed us to gain more insight into what these planets are. Virtually all Neptunes, Jupiters and super-Jupiters turned out to have extended hydrogen-dominated atmospheres. Indeed, it appears that seemingly all planets larger than 1.8 R_{Earth} host extended, hydrogen-dominated atmospheres, but there are significant differences between Jupiter-mass planets and planets close to the border of the super-Earth class.

While Jupiter-mass planets are gas-giants for which much of the mass is contained inside the Hydrogen/Helium dominated envelope, for the so-called mini-Neptunes, instead, the Hydrogen/Helium dominated envelope contains just 1-2% of the total mass of the planet. Mini-Neptunes are thus not gaseous planets, but rocky planets with extended envelopes. In a few cases it was shown that the atmospheres of mini-Neptunes are hybrid atmosphere containing hydrogen and a substantial amount of elements heavier than Hydrogen and Helium (García Muñoz et al. 2021). The density measurements of low-mass planets imply that there are three populations: rocky, water-rich, and gas-rich planets (Luque & Pallé 2022).

Close-in planets (a<0.1 AU) with radii smaller than 1.4 $R_{\rm Earth}$ are rocky without an extended atmosphere and close-in planets with radii larger than 1.8 R_{Earth} are mini-Neptunes. Close-in planets with radii between 1.4 and 1.8 $R_{\rm Earth}$ are rare (Fulton & Petigurea 2018; Owen & Wu, 2013; Jin et al., 2014; Lopez & Fortney, 2014; Fridlund et al. 2020). Surprisingly, the masses of super-Earths are almost the same as for mini-Neptunes. These results are very surprising. Why do some low-mass planets have extended hydrogen atmospheres, and others not? Furthermore mini-Neptunes and super-Earths are the most common type of planet, but we do not have any such planet in the solar-system.

The fact that some of these planets have extended atmospheres, while others do not, must be related to their formation and evolution history. Several possible mechanisms have been proposed. One process is atmospheric erosion (e.g. Lammer et al. in 2014). Another possibility is gas-poor formation (e.g. Owen & Wu, 2013; Lee et al. 2022). More recently, Venturini et al. (2020) presented a model in which a planet grows from a moon-mass embryo by either silicate or icy pebble accretion, followed by type I-II migration, and photoevaporation driven mass-loss. Atmospheric erosion could either be caused by photoevaporation due to the X-ray and EUV (together XUV) irradiation from the host-star, or by atmospheric escape due to formation heating (i.e. core powered mass-loss; e.g. Izidoro et al. 2022). However, even if gas-poor formation or formation heating were the dominant processes, atmospheric erosion due to the XUV irradiation from the host star would still play an important role. Tian & Heng (2023) have shown that hybrid atmospheres are a natural outcome of the evolution in atmospheres of close-in, low-mass planets.

2. Evidence for mass-loss

Arguably, the best studied cases for atmospheric erosion are the hot Jupiters HD 209458 b and HD 189733 b. The detection of atomic hydrogen beyond the Roche lobe first established that atmospheric material was escaping from HD 209458 b. Estimated escape rates for HD 209458 b are of the order of 10^{10}-10^{11} $\rm g\,s^{-1}$ (e.g. Vidal-Madjar et al. 2003, García Muñoz 2007) and 10^9 - 10^{11} $\rm g\,s^{-1}$ for HD189733b (e.g. Lecavelier Des Etangs et al. 2010). Therefore, both hot

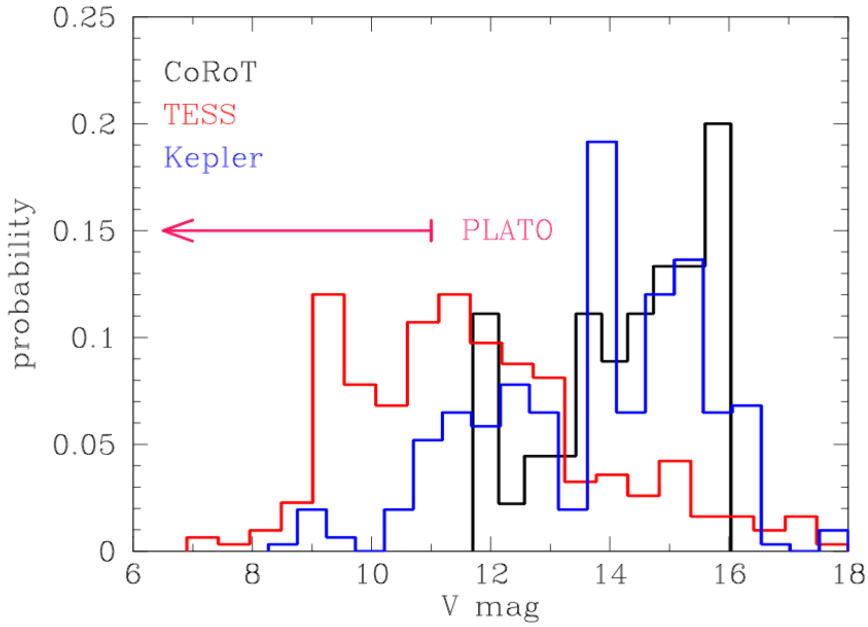

Figure 1. Brightness in V of the planet host stars discovered by CoRoT, Kepler and TESS. The P1 sample of PLATO contains host stars between V=4 and V=11.

Jupiters loose about 0.1 to 0.2% of their mass per Gyr. Thus, the observed atmospheric escape of the gas-giants is not large enough to fully erode these planets to their rocky cores.

Since the Hydrogen/Helium atmosphere of a mini-Neptune contains only 1-2% of the total mass of the planet, mass loss becomes critically important for low-mass planets. Since the amount of XUV radiation of a solar-like star with an age of 10 Myrs is 300 to 1500 times higher than that of the current Sun, the main erosion phase occurs when the star is young (e.g. Ketzer & Poppenhaeger 2023). Therefore, it is possible that the Hydrogen/Helium atmosphere of a min-Neptune is completely eroded in the first few Myrs. For example, V1298 Tau is a young star with four transiting exoplanets for which Poppenhaeger et al. (2021) showed that the innermost two planets may lose their hydrogen-dominated atmospheres to become rocky planets. Another interesting case is K2-33b, a young planet in Upper Sco, which may lose its entire hydrogen atmosphere if the planet has less than 7-10 $M_{\rm Earth}$ (Kubyshkina et al. 2018). HST observations of the Neptune-sized planet GJ3470b show an evaporation rate $10^{10}\,{\rm g\,s^{-1}}$. The planet may have already lost about 35% of its mass (Bourrier et al. 2018). Kepler-1520 b (=KIC 12557548 b) may have lost $\sim$ 70% of its formation mass, today we may be observing its naked iron core (Perez-Becker & Chiang 2013). However, the erosion rates of planets with hybrid atmospheres are lower than those of pure Hydrogen-dominated atmospheres (Tian & Heng 2023).

3. The observing strategy

Mass loss certainly is a key factor in the evolution of a planet. In the case of WASP-12 b Haswell et al. (2012) detected the gas escaping from this heavily irradiated planet. They observed the planet in the UV and found that the transit is three times deeper than in the optical, indicating the presence of diffuse gas, extending well beyond the Roche lobe. They also found that surprisingly the MgII h&k line cores have zero flux indicating that the inner portions of these strong resonance lines are likely affected by extrinsic absorption due to the material escaping from the planet (Fossati et al. 2013). There is thus strong evidence for mass loss for WASP-12b.

Mass loss from a close-in planet can form a diffuse circumstellar gas cloud, which absorbs in the cores of strong resonance lines (e.g. CaII H&K and MgII h&k) seemingly suppressing the signatures of stellar activity below their true value (Haswell et al. 2012; Fossati et al. 2013). Simulations show that the density of the material in the torus is inhomogeneous (Bell et al. 2019; Dwivedi et al. 2019; Zhang et al. 2023). Observations of the Helium triplet line at 1083.3 nm during roughly a quarter of the orbit by Zhang et al. et al. (2023) indicate the material forms a torus.

Since the density of the material in tours varies along the orbit of the planet, the strength of the CaII H&K lines should also vary. By observing several orbits, it is then possible to reconstruct the density of material in the torus. However, if we observe only the CaII H&K lines, we would only constrain how much Ca has escaped from the planet. The strength of the absorption would depend on the amount of Ca that the envelope contains. Using not only the CaII H&K lines but also Hα and NaD it would be possible to determine the physical properties of the torus, for example, how much mass it contains. In this way it would be possible to "see" the material that is escaping from the planet.

Shkolnik et al. (2003, 2005, 2008) have studied the chromospheric activity in the Ca II H and K lines with the aim to search for induced stellar activity. A spectralline that originates from the star has width that is of the order of the v sin i of the host star, depending on the location of the active region on the stellar surface. The RV-amplitude of a close-in planet is much larger than that. A ring of material the originates from material that has escaped from a close-in planet will have a width that corresponds to the RV-amplitude of the planet. Such a feature will thus be much broader than a stellar spectralline.

4. Preparing for PLATO and planed observations

The question is whether there are already good targets for such a project. Because the absolute mass-loss of gas-giants are larger than that of min-Neptunes, gas-giants are the preferred targets. Table 1 gives a list of nineteen known planets in the mass-range between Mp = 0.5 and 5.0 M_{Jup} with Rp $\geq$ 1.4 R_{Jup} orbiting stars with V $\leq$ 11 mag that are observable from La Silla [1]. As can be seen, all of these targets are short-period planets. The large radii are thus most likely due to large heating by the host star. Thus, these planets are likely to have also a large mass-loss rate. For comparison WASP-12 b has Rp = 1.47 M_{Jup}, Mp = 1.9 M_{Jup} (Collins et al. 2017).

While many bright stars hosting close-in gas-giant have already been identified it would be even more exciting if bright stars hosting close-in Neptunes were found. Absolutely thrilling would be the discovery of planets like those of V1298 Tau (V=10.1 mag), GJ3470b (G=11.4 mag), or K2-33b (G=14.1 mag), K2-240 (V=13.4 mag) but orbiting brighter stars.

What are the prospects to find planets like that but orbiting brighter stars? The key to find these is the PLATO mission. PLATO (PLAnetary Transits and Oscillation of stars) will search for extrasolar planets by means of ultra-high-precision transit photometry. PLATO consists of 24 normal and 2 two high cadence cameras providing combined wide field of view (FoV) of 49x49 square degrees. The PLATO mission and the key-science goals are summarized in Rauer et al. (2014, 2021).

The first PLATO field has now been selected [2]. The center is at RA: 06:21:14.5 DE: -47:53:13. This field contains more than 9000 dwarf and subgiant stars of spectral types from F5 to K7 with V <11 mag (P1 sample) that will be observed. The random noise of the P1-sample will be lower than 50 ppm in one hour. Fig. 1 shows the brightness of planet host stars discovered in the CoRoT, Kepler and TESS mission, respectively [3]. AS can be seen in the figure, one of the advantages of PLATO compared with previous missions is that planet host stars will be much brighter. The baseline observing strategy assumes that this field will be observed for at least two years. The PLATO spacecraft has been designed to perform scientific operations for at least 8.5 years. PLATO will also observe more than 159,000 dwarf and subgiant stars of spectral types from F5 to K7 with mV < 13.

Ondrejov observatory, the Thüringer Landessternwarte Tautenburg and the Pontificia Universidad Católica de Chile as main partners have a unique access to the ESO1.5m telescope in La Silla (Chile). Minor partners are the IGAM of the university of Graz, Universidad Adolfo Ibanez and Masaryk University. The telescope has recently been refurbished. It is fully operational and currently

[1] Objects selected using https://https://exoplanet.eu
[2] See https://www.cosmos.esa.int/web/plato/first-sky-field
[3] Figures produced using https://https://exoplanet.eu

equipped with the PUCHEROS Echelle spectrograph that has a resolution of R=20,000. By the end of 2024, we will install PLATOspec, which is a state-of-the-art UV-optimised high-resolution Echelle spectrograph with a resolution of R=68,000 covering the 360-680 nm spectral range without gaps. The high UV throughput of the spectrograph, which is rather unique in the current instrumental landscape, enables one to collect high-quality spectra throughout the entire optical band, including the CaII H&K lines, the NaI D lines, and the Hα line. The spectrograph will be fibre fed and will be placed in a temperature-stabilized room.

As the name of the instrument already suggest, its main purpose will be the follow-up observations of transiting planets discovered in the PLATO mission. Because of the relatively large amount of observing time required this instrument is ideal to carry the project.

Table 1. Inflated gas-giant planets observable from La Silla orbiting stars brighter than 11 mag in V.

Star	RA2000 (hh:mm:ss)	DE2000 (dd:mm:ss)	V [mag]	Mass [M_{Jup}]	Radius [R_{Jup}]	Period [days]	K [m/s]
HIP65A	00:00:45	-54:49:51	11.1	3.213 ± 0.078	$2.03^{+0.61}_{-0.49}$	0.98	754
HD2685	00:29:19	-76:18:15	9.6	1.18 ± 0.09	1.44 ± 0.01	4.13	118
WASP-76	01:46:32	+02:42:02	9.5	0.92 ± 0.03	1.83 ± 0.06	1.81	119
WASP-79	04:25:29	-30:36:02	10.1	0.9 ± -0.09	1.7 ± 0.11	3.66	88
WASP-100	04:35:50	-64:01:37	10.8	2.03 ± 0.12	1.69 ± -0.29	2.85	215
WASP-82	04:50:39	+01:53:38	10.1	1.24 ± 0.04	$1.67^{+0.07}_{-0.05}$	2.71	130
TOI-640	06:38:56	-36:38:46	10.5	0.88 ± 0.16	1.771 ± 0.06	5.00	78
WASP-121	07:10:24	-39:05:51	10.4	$1.184^{+0.065}_{-0.064}$	1.865 ± 0.044	1.27	181
KELT-17	08:22:28	+13:44:07	9.6	1.31 ± 0.29	$1.525^{+0.065}_{-0.06}$	3.08	131
HAT-P-69	08:42:01	+03:42:38	9.8	3.58 ± 0.58	$1.676^{+0.051}_{-0.033}$	4.79	309
TOI-2669	08:58:53	-13:18:45	9.5	0.61 ± 0.19	1.76 ± 0.16	6.20	60
HD85628A	09:50:19	-66:06:50	8.6	3.1 ± 0.9	$1.53^{+0.07}_{-0.04}$	2.82	307
WASP-15	13:55:43	-32:09:35	10.9	0.542 ± 0.05	1.428 ± 0.077	3.75	63
NGTS-2	14:20:30	-31:12:07	11.0	0.67 ± 0.089	1.536 ± 0.062	4.51	69
WASP-189	15:02:44	-03:01:53	6.6	$1.99^{+0.16}_{-0.14}$	1.619 ± 0.021	2.72	182
WASP-88	20:38:03	-47:32:17	10.4	0.56 ± 0.08	$1.7^{+0.13}_{-0.07}$	4.95	57
MASCARA-1	21:10:12	+10:44:20	8.3	3.7 ± 0.9	1.5 ± 0.3	2.15	405
HD202772A	21:18:48	-26:36:59	8.3	$1.008^{+0.074}_{-0.079}$	$1.562^{+0.053}_{-0.069}$	3.31	97
WASP-11	21:55:04	-22:36:45	10.3	1.85 ± 0.16	1.442 ± 0.094	2.31	212

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