Atmospheric mass loss of extrasolar planets orbiting magnetically active host stars

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ABSTRACT
Magnetic stellar activity of exoplanet hosts can lead to the production of large amounts of high-energy emission, which irradiates extrasolar planets, located in the immediate vicinity of such stars. This radiation is absorbed in the planets’ upper atmospheres, which consequently heat up and evaporate, possibly leading to an irradiation-induced mass-loss. We present a study of the high-energy emission in the four magnetically active planet-bearing host stars Kepler-63, Kepler-210, WASP-19, and HAT-P-11, based on new XMM-Newton observations. We find that the X-ray luminosities of these stars are rather high with orders of magnitude above the level of the active Sun. The total XUV irradiation of these planets is expected to be stronger than that of well-studied hot Jupiters. Using the estimated XUV luminosities as the energy input to the planetary atmospheres, we obtain upper limits for the total mass loss in these hot Jupiters.

Key words: stars: activity – stars: coronae – stars: low-mass, late-type, planetary systems – stars: individual: Kepler-63, Kepler-210, WASP-19, HAT-P-11

1 INTRODUCTION

The discovery of the first exoplanet 51 Peg b, orbiting around a Sun-like star, by Mayor & Queloz (1995) has become the starting point of a new research area in astrophysics, i.e., exoplanetary science. Many more discoveries quickly followed, and in 2002 the first detection of an atmosphere around an exoplanet (HD 209458 b) was accomplished (Charbonneau et al. 2002). Since then both the methods of detecting exoplanets and the ability to characterize their physical properties have made rapid progress. The lower mass limit of detected exoplanets has constantly decreased and the detection of low-mass planets, i.e., the super-Earths with masses in the range of 1-10 Earth masses, has now become possible. Naturally, the goal is to ultimately detect an Earth-like planet within the stellar habitable zone, i.e., that zone which allows the presence of liquid water on the planet’s surface; that goal has been recently bolstered by the discovery of seven Earth-like planets around Trappist-1, three of which fall in the habitable zone (Gillon et al. 2017).

For the habitability of a planet, its ability to hold an atmosphere of its own for a significantly long period of time is of paramount importance. While it was originally thought that atmospheric losses in exoplanets occur predominantly through Jeans escape, the observations of atmospheric mass loss in HD 209458 b (Vidal-Madjar et al. 2003) show that this process can grossly underestimate the actual mass loss. In a seminal paper, Lammer et al. (2003) hypothesize that exoplanets may lose their atmospheres through a different mechanism, which relies on a hydrodynamic mass loss model originally proposed by Watson et al. (1981) and can give rise to orders of magnitude larger mass loss rates. In this model the high-energy radiation is absorbed in the upper layers of the planetary atmosphere, which consequently heat up to temperatures in excess of 10,000 K, leading to a hydrodynamic outflow similar to the classic Parker model of the solar wind. The calculation of the atmospheric mass loss in this model context thus requires an assessment of the exoplanetary high-energy environment and in particular, the amount of X-ray, FUV and UV radiation it receives from its host star. Furthermore, several chemical processes like photochemical decomposition, charge exchange and sputtering are induced, all of which can contribute to the mass loss. Lammer et al. (2003) and Sanz-Forcada et al. (2010) show that this mechanism can produce mass loss rates which are corroborated by observations of actual exoplanetary mass loss in hot Jupiters with large amounts of hydrogen and helium in their atmospheres.

With the here presented study of hot-Jupiter hosts, we provide a small sample of rather active stars, where the ef-
fects of planetary evaporation are expected to be very large. With our exploratory X-ray observations we obtain a better insight into the hottest parts of the outer stellar atmospheres of these planet hosts. Our analysis specifically allows us to estimate the coronal temperature and the X-ray activity level of these stars, which in turn allow us to calculate rough estimates of the mass loss of the orbiting exoplanets. In §2 we describe our target stars, in §3 we describe the XMM-Newton observation, our data analysis and our results. A discussion and our conclusions are presented in §4.

2 THE SAMPLE STARS

In this article, we present the results of new XMM-Newton X-ray observations of four hot-Jupiter hosts, i.e., the stars Kepler-63, Kepler-210, WASP-19, and HAT-P-11. All these target stars are in the Kepler planetary candidate sample for host stars with excess photometric modulation (~1%), i.e., they are presumably very active with large amounts of high-energy radiation produced; we list all the known properties of the investigated host stars and their exoplanets in Tab. 1. In the following, we provide a more detailed description of our sample stars.

2.1 Kepler-63

Kepler-63 is a young Sun-like star (~0.21±0.04 Gyr, Sanchis-Ojeda et al. 2013; Estrela & Valio 2016) at a distance of 200±15 parsec with a mass of 0.98M⊙, effective temperature of 5576 K (Sanchis-Ojeda et al. 2013) and a rotation period of 5.4 days (Estrela & Valio 2016). The data presented by Sanchis-Ojeda et al. (2013) suggest that Kepler-63 has a rather high level of chromospheric activity (measured in Ca II H&K) with log R′HK = −4.39; one also observes quasi-periodic stellar flux variations on the order of ~4%, interpreted as rotational modulation by starspots. Furthermore, based on spot modeling from the Kepler data, Estrela & Valio (2016) argue for the existence of a magnetic activity cycle of 1.27±0.16 years in Kepler-63.

Kepler-63 hosts a hot Jupiter with a radius of 6.1±0.2 R⊕ in a polar orbit with a relatively short orbital period of 9.434 days and a semi-major axis of 0.08 AU (Sanchis-Ojeda et al. 2013). The mass of the planet is not known very precisely because its radial velocity data are contaminated by the high activity level of the host star. However, the RV data suggest a semi-amplitude value of approximately 15-20 m/s, which leads to an upper limit of 120 M⊕ for the mass of Kepler-63b. (Sanchis-Ojeda et al. 2013). Based on these values for mass and radius, the upper limit for the planet’s mean density is ρp < 3.0 g/cm³ (Sanchis-Ojeda et al. 2013).

2.2 Kepler-210

Kepler-210 is a young active K-dwarf with a period of 12.33 days and an estimated age of 350±50 Myr (Ioannidis et al. 2014); the activity of Kepler-210 is shown by the large modulations in the observed Kepler light curve. Kepler-210 hosts at least two Neptune-sized planets, Kepler-210b with a radius of 3.75±0.03 R⊕ and a period of 2,453 days, and Kepler-210c with a radius of 4.78±0.04 R⊕ and a period of 7,972 days (Ioannidis et al. 2014). According to Ioannidis et al. (2014), these planets orbit at distances of 0.014 AU and 0.037 AU, respectively. No radial velocity data are available for the system and hence the masses of the planets are not known. However, using the simple mass-radius relationship $M_p = \left(\frac{R_p}{R_\oplus}\right)^{2.06} M_\oplus$ given by Lissauer et al. (2011), which holds reasonably well for planets smaller than Saturn, we may estimate the masses at least to within some factors and hence can provide mass loss estimates correct to an order of magnitude. Using this relation we find the masses of Kepler-210b and Kepler-210c to be 15.92 M⊕ and 26.27 M⊕ respectively, leading to mean density values of 1.66 g/cm³ and 1.32 g/cm³ respectively. Ioannidis et al. (2014) also argue that the densities of these planets are below 5 g/cm³, with both planets having a mass upper limit of 0.5 Mj.

2.3 WASP-19

WASP-19 is an active G8V type star (log R′HK = −4.66, Knutson et al. 2010) with a mass of 0.96 M⊕, a radius of 0.94 R⊕ and a surface gravity log g of 4.47±0.03 (Hebb et al. 2010). WASP-19 shows strong rotational modulation with a period of 10.5 days and, according to the gyrochronology relationship given by Barnes (2007), this short period indicates that the system is relatively young (~600 Myr old). On the other hand, the estimated system age of 5.5±0.9 Gyr derived by Hebb et al. (2010) using isochrone fitting and adopting a zero eccentricity value, is at least formally larger, yet the errors of this estimate are huge.

The orbiting exoplanet around WASP-19 is the largest objects in our sample with a radius of 15.21 R⊕ and a mass of 371 M⊕, making it even larger than Jupiter. WASP-19b has a short orbital period of only 0.7888 days, leading to a very small distance between host star and planet of 0.0162 AU. The mean density calculated from these mass and radius values is 0.58 g/cm³ and the mean density estimated by Hebb et al. (2010) is about 0.51±0.06 g/cm³. However, it is interesting to note that the mean density of WASP-19b is just half that of Jupiter, suggesting that the planet could be slightly bloated for its mass. The enhanced radius of WASP-19b could be interpreted as a result of the high-energy irradiation from the host star or tidal energy dissipation.

2.4 HAT-P-11

HAT-P-11 is an active metal-rich K4 dwarf star ([Fe/H] = +0.31±0.05) located at a distance of 38 pc. Using spectroscopic and photometric data, Bakos et al. (2010) estimated the mass, radius, temperature and age of HAT-P-11 to be 0.81 M⊙, 0.75 R⊙, 4780±50 K and 6.5±5.3 Gyr respectively. Based on the Kepler photometric data, the stellar activity for HAT-P-11 is indicated by spot induced modulations (Sanchis-Ojeda & Winn 2011; Deming et al. 2011). The star also shows strong chromospheric emission (measured in Ca II H&K) with an S-index of 0.61 and log R′HK = −4.585 (Bakos et al. 2010), indicating again that the star is active.

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HAT-P-11 hosts a super-Neptune with a radius of 4.96 $R_\oplus$, a mass of 25.74 $M_\oplus$ and a mean density of $\sim 1.33 g/cm^3$, orbiting at a distance of 0.053 AU with a period of 4.887 days (Bakos et al. 2010). When comparing to the models of Fortney et al. (2007), Bakos et al. (2010) note that, first, the radius of HAT-P-11b appears to be much smaller than that of a planet with similar mass and consisting of a 50% ice/rock core and a 50% H/He envelope; and that, second, it is much larger than a planet with a pure ice/rock core without any H/He gaseous envelope. Therefore Bakos et al. (2010) argue on the basis of several parameters such as irradiation, distribution of heavy elements, age, etc., that HAT-P-11b is more likely a super-Neptune planet with $Z=0.9$ and 10% H/He envelope.

3 DATA ANALYSIS AND RESULTS

The data presented in this paper have been obtained with the XMM-Newton satellite, an observation log of our observation is contained in Tab. 1. All X-ray data were reduced with the XMM-Newton Science Analysis System (SAS) software, version 15.0.0; EPIC light curves and spectra were obtained using standard filtering criteria and spectral analysis was carried out with XSPEC version 12.9.0 (Arnaud 1996).

To provide an impression of the data and their quality we show the soft X-ray images from the merged EPIC data in Fig. 1. Clearly, X-ray emission from all sample stars is detected, but with different strengths. The source signals in case of Kepler-63 and HAT-P-11 were taken from Bakos et al. (2010). The mean planetary densities are used to infer the composition and internal structure of orbiting exoplanets (Baraffe et al. 2008; Fortney & Nettelmann 2010; Swift et al. 2012; Spiegel et al. 2014).
Figure 2. Light curves of Kepler-63, Kepler-210, WASP-19 and HAT-P-11 observed by EPIC detectors. The hardness ratio is plotted in lower panel.

3.1 Temporal analysis

As can be clearly seen in Fig. 1, the XMM-Newton observations indicate obvious X-ray detections of all four host stars. Consequently, we carry out a more detailed temporal study of each of our targets and produce the X-ray light curves shown in Fig. 2. The reduced PN data of Kepler-63 and HAT-P-11 in the 0.2-2.0 keV energy band are binned at 800 s. However, to enhance the signal we combine (in the cases of Kepler-210 and WASP-19) all the EPIC data and bin at 1500 s in the energy range of 0.2-2.0 keV. In the top panel of Fig. 2, we show the source light curves, and in the bottom panel the measured hardness ratio (HR) values vs. time; HR is defined as the fractional difference between hard energy band and soft energy band photon counts through the expression $HR = \frac{H - S}{H + S}$, where $H$ is the number of counts between 0.7 and 2.0 keV (hard band) and $S$ the number of counts between 0.2 and 0.7 keV (soft band). The mean $HR$-values determined from the PN data for Kepler-63 and HAT-P-11 are $0.37 \pm 0.11$ and $0.34 \pm 0.30$ respectively, while those derived for Kepler-210 and WASP-19 from the EPIC data are $0.22 \pm 0.27$ and $0.12 \pm 0.16$, respectively. The derived HR-values are consistent with each other to within the errors and we observe no significant changes in count rate nor in HR, suggesting that the targets were observed in a state of quiescence.

3.2 X-Ray luminosities of exoplanet hosts

For Kepler-63 and HAT-P-11, the number of counts measured in the MOS and pn cameras is sufficient for a more detailed spectral analysis. In Fig. 3 we show the PN spectra for Kepler-63 and HAT-P-11 with their respective best-fit models; the HAT-P-11 spectrum in Fig. 3 is shifted upwards by an order of magnitude for better visibility. A two-component APEC with solar abundance (Grevesse & Sauval 1998) provides a robust fit, the results of which are listed in Tab. 2, which also gives the resulting X-ray fluxes and luminosities in the 0.2-2.0 keV band. We also experimented with treating the coronal abundances as a free parameter, but this did not significantly improve the fit and we conclude that the metallicity can be only poorly constrained with the avail-
available data. Furthermore, since Kepler-63 is at a distance of 200 pc, we also allow the absorption to vary freely and obtain an equivalent hydrogen column of 9.4^{+5.6}_{-6.2} \times 10^{20} \text{ cm}^{-2}; obviously the data quality is not sufficient to constrain the amount of interstellar absorption along the line of sight towards Kepler-63 very well. Inspection of Tab. 2 shows that Kepler-63 is hotter and more X-ray luminous (2 \times 10^{29} \text{ erg/s} ) than HAT-P-11 and in particular the Sun, indicating that Kepler-63 is indeed very active.

For Kepler-210 and WASP-19 we do not have sufficient counts for a meaningful spectral analysis, rather we use the HR-values to determine the coronal temperatures of the stars. Using a two-component APEC (Astrophysical Plasma Emission Code) coronal plasma model for a collisionally ionised optically-thin thermal plasma (Smith et al. 2001) with solar abundances, we calculate the theoretical HR values as a function of temperature. We performed the spectral analysis using XSPEC version 12.9.0 (Arnaud 1996). We estimate the coronal temperature of Kepler-210 to lie between 2.5 and 4.1 MK and that of WASP-19 between 3.3 and 5.3 MK. Using the estimated coronal temperatures in WebPIMMS, we convert the mean count rate measured with the XMM-Newton PN detector into an X-ray flux in the 0.2-2.0 keV energy band. Both Kepler-210 and WASP-19 are at distances >200pc, where the interstellar hydrogen might produce a significant absorption of the X-ray flux. We assume a hydrogen column depth of N(HI + H2)=10^{21} \text{cm}^{-2} with a canonical density of 1 particle per cm$^3$ (Ferlet et al. 1985; Cox 2005; Welsh et al. 2010). We are aware that the hydrogen column density is not homogenous along all directions. Using a distance of 250 pc and 265 pc for WASP-19 and Kepler-210, respectively, the unabsorbed fluxes obtained using WebPimms are converted into the X-ray luminosities (see Tab. 3).

The bolometric luminosity of our candidates can be calculated through the relation \( L_{\text{bol}} = 10^{0.4(4.74-m_B-BC+5\log(d)-5)M_\odot} \), where \( m_B \) denotes the apparent visual magnitude of the star, \( BC \) the bolometric correction, \( d \) the distance (in pc) and \( M_\odot \) the solar bolometric luminosity. For Kepler-63, WASP-19 and HAT-P-11 the values for the V and K magnitudes are obtained from the SIMBAD database. For Kepler-210, we use the B-V color from Ioannidis et al. (2014) and convert it into a V-K color using the data provided in Worthey & Lee (2011); the bolometric corrections are determined using the relationship given by Worthey & Lee (2011). The results of our analysis for all the targets are listed in Tab. 3. The computed log \( F_X \)-ratios indicate again stars of moderate activity with the exception of Kepler-63.

| Parameters | Kepler-63 | HAT-P-11 | Unit |
|------------|-----------|----------|------|
| \( T_1 \) | 0.43^{+0.04}_{-0.05} | 0.14^{+0.08}_{-0.10} | keV |
| \( EM_1 \) | 44.61^{+22.78}_{-15.87} | 1.45^{+0.27}_{-0.23} | 10^{50} \text{ cm}^{-3} |
| \( T_2 \) | 1.08^{+0.22}_{-0.23} | 0.64^{+0.13}_{-0.11} | keV |
| \( EM_2 \) | 14.09^{+4.30}_{-6.71} | 0.35^{+0.09}_{-0.10} | 10^{50} \text{ cm}^{-3} |
| \( N_H \) | 9.4^{+5.8}_{-6.2} | \text{--} | \text{10}^{20} \text{ cm}^{-2} |
| \( \chi^2_{\text{red}}(d.o.f) \) | 0.92 (25) | 0.87 (12) | |
| \( F_X \) (0.2-2.0 keV) | 2.35^{+0.67}_{-0.55} | 2.77^{+0.15}_{-0.13} | 10^{-14} \text{ erg/s/cm}^{-2} |
| \( L_X \) (0.2-2.0 keV) | 10.06^{+3.27}_{-2.67} | 0.47^{+0.11}_{-0.10} | 10^{28} \text{ erg/s} |

3.3 Stellar radiation at the planetary positions

As indicated at the end of the previous subsection, the log \( F_X \)-values for our sample stars lie between -4.36 and -5.57. Given these activity levels and the fact that the planets are close to their host stars, makes all of them likely to undergo atmospheric loss through hydrodynamic escape. As shown by Lammer et al. (2003), such mass loss occurs predominantly due to radiation in the EUV and X-ray range. From our XMM-Newton observations only X-ray wavelengths are accessible, hence we need to apply an indirect method to obtain the total high-energy radiation in the X-ray and UV-bands. Sanz-Forcada et al. (2011) compute the EUV spectra for a number of stars using the emission measure distribution derived from X-ray spectra. This approach has been shown to be quite accurate by further studies by Claire et al. (2012) and Linsky et al. (2013). However, we do point out in this context that France et al. (2016) argue that FUV flux estimates based on soft X-ray emission alone can substantially underestimate the irradiation received by extrasolar planets in individual cases; since no detailed FUX/XUV studies are available for our target stars, there is nothing we can do about this at the moment. Using the scaling relations given by Sanz-Forcada et al. (2011) we extrapolate the measured X-ray luminosity to the total high-energy radiation viz.

\[
\log L_{\text{EUV}} = (0.860 \pm 0.073) \log L_X + (4.80 \pm 1.99)
\]

and

\[
\log L_{\text{XUV}} = \log(L_X + L_{\text{EUV}}).
\]

3.4 Estimated atmospheric mass loss of planetary candidates

According to the hydrodynamic mass loss model as developed by Watson et al. (1981), Lammer et al. (2003),
Sanz-Forcada et al. (2010) and Erkaev et al. (2007), the planetary mass loss rate $\dot{M}$ is given by
\[ \dot{M} = \frac{3\gamma \beta^2 \epsilon F_{XUV}}{4G\rho_p}, \quad (3) \]
where $\rho_p$ is the mean planetary density, $F_{XUV}$ the incident X-ray+EUV flux, and $G$ the gravitational constant. The term $\beta = R_{XUV}/R_p$ is a correction factor for the size of the planetary disk absorbing the XUV radiation. Salz et al. (2016a) provide an estimate for $\beta$ through
\[ \log \beta = \max(0.0, -0.185 \log(-\phi_G) + 0.021 \log(F_{XUV}) + 2.42), \quad (4) \]
where $\phi_G = -GM_p/R_p$ is the gravitational potential at the surface of the planet. We assume an heating efficiency $\epsilon = 0.4$ (in Eqn. 3) as suggested by Valencia et al. (2010) for hot Jupiters and strongly irradiated rocky planets. Several authors choose values of $\epsilon < 0.4$ (Owen & Jackson 2012; Shematovich et al. 2014), based on observations of evaporating hot Jupiter HD 209458b. Furthermore, Salz et al. (2016a) show that small planets like HAT-P-11 do not show trend in the heating/evaporating efficiency and hence using a constant value of $\epsilon$ is a reasonable approximation. Note that the value of $\epsilon$ is only a rough estimate, however, in reality, the heating efficiency can be determined more precisely only after modeling the atmosphere of exoplanets in detail.

The parameter $K$ in Eqn. 3 is a factor which takes into account the effects of mass loss through Roche lobe overflow. According to Erkaev et al. (2007), $K$ is given by
\[ K(\eta) = 1 - \frac{2}{\sqrt{\eta}} + \frac{1}{2\eta}, \quad (5) \]
where the parameter $\eta$ is given by
\[ \eta = \left( \frac{M_p}{3M_\star} \right)^{1/3} a / R_p. \quad (6) \]
Here $M_p$ and $M_\star$ denote planetary and stellar masses respectively, $a$ is the semi-major axis and $R_p$ the planetary radius. This expression is approximate and valid only if $a >> R_{RI} > R_p$ (where $R_{RI}$ is the Roche lobe radius of the planet) and $M_\star > M_p$ hold. Following Erkaev et al. (2007) and taking $R_{RI}$ as
\[ R_{RI} = a \left( \frac{M_p}{3M_\star} \right)^{1/3}, \quad (7) \]
we find $\eta = R_{RI}/R_p$. Since $R_{RI}$ is usually much larger than the radius $R_p$, $K(\eta)$ approaches unity.

With the above equations, the planetary parameters listed in Tab. 1 and the observed X-ray luminosity of the planet host stars, the upper-limit mass loss rates can be estimated. We note that the mass-loss rates are derived assuming a constant density. The mass loss induced by the incident high-energy radiation will in general also change the radius of the planet, since mass and radius are coupled, once the composition and equation of state for the interior are known. Lopez & Fortney (2014) studied in detail the change in the radius of the planet as a function of its mass for different planetary compositions and in particular for different contributions of a H/He envelope. Since the compositions of the planets studied in this paper are not known, we assume the simplest model of a constant mean density of the planet to estimate the mass-loss history. We also note that the changing incident XUV flux provides the by far dominant component for driving the mass loss.

Stellar activity, especially for young stars is not constant over the lifetimes of the stars. In fact, according to Ribas et al. (2005) the X-ray luminosity varies approximately by a factor of $\left( \frac{T}{T_\star} \right)^{-1.23}$, where $T$ is the current stellar
age and $\tau_*$ is the stellar age, at which stellar activity remains at a constant level (at about 0.1 Gyr), which is also taken as the start time for the integration of the mass loss. For single stars, the coronal activity is highest when the star has – more or less – finished its contraction, but has not yet spun down, so that the large stellar rotation yields very high levels of activity (Sanz-Forcada et al. 2014); hence we choose as starting time an age of 0.1 Gyr. Inserting this time variable flux into the hydrodynamic mass loss equation and integrating it over time, provides a coarse estimate of the mass loss history of these planets. The results are listed in Table 3.

According to our estimates, both Kepler-210 b and c have suffered very little mass loss below 0.1 M$_J$. However, Kepler-63 b has suffered an mass loss of possibly up to 0.5 M$_J$. The age-activity relationship for stars older than 1 Gyr are steeper and are given by the relation $\log \frac{L_X}{(R_*/K_*)^2} = 5.65 \pm 0.98 - (2.80 \pm 0.72) \log \tau$ (Booth et al. 2017). We calculate the maximal mass loss for HAT-P-11 b to lie in the range between 0.15-0.25 M$_J$, using both the age-activity relations given by Ribas et al. (2005) and Booth et al. (2017). Furthermore, the large uncertainty on the age of HAT-P-11 which can contribute significantly to estimated mass-loss of the orbiting planet.

Similar to HAT-P-11, there are huge uncertainties in the proposed ages of WASP-19 which ranges from under 1 Gyr to more than 5 Gyr. In Figure 4, we plot the total mass lost integrating over stellar ages between 0.6-5.5 Gyr, where each curve represents a different age of the WASP-19 systems. Considering the large uncertainty in the age of WASP-19, we estimate a total mass loss of 0.1-3 M$_J$. However, assuming an age of WASP-19 of ~2.2 Gyr (Brown et al. 2011) by comparing the X-ray luminosity of WASP-19 with the age-X-ray luminosity relation, we estimate the maximal mass lost by the planet to be between ~0.9-1.0 M$_J$.

![Figure 5](image_url)

**Figure 5.** log $M$ vs. Mass for solar system gaseous giant planets (filled squares) and our sample exoplanets (filled circle with downward arrow). The three well-studied hot-Jupiter systems HD 189733, HD 209458 and CoRoT-2 are additionally shown as filled stars. All values of log $M$ are upper limit estimates using $\epsilon = 0.4$ and assuming $K = 1$ without any magnetosphere. Using the mass-radius relationship given by Lissauer et al. 2011, we estimate the masses of Kepler-210 b and c.

## 4 DISCUSSION AND CONCLUSIONS

Here we report the results of exploratory X-ray studies of the four transiting active exoplanet hosts Kepler-63, Kepler-210, WASP-19 and HAT-P-11 in the soft X-ray energy band 0.2-2.0 keV, which yield detection with logarithmic X-ray luminosities in the range from 2.68-29.05 erg s$^{-1}$. The XMM-Newton pointing were rather short and allow only a rather coarse characterization of the X-ray properties of the host stars. All the target stars show an X-ray activity indicator $\log \frac{L_{bol}}{L_X}$ in the range between -4.36 to -5.57, which combined with coronal temperatures in the range 3.0 and 8.0 MK, points to moderately active to active stars. Our analysis suggests that the X-ray properties of Kepler-63 are compatible with the presence of strong Ca II H&K emission cores and spot modulation. Using the measured X-ray luminosities, we infer the irradiation fluxes at far UV wavelengths allowing us to estimate the XUV flux at the planetary position and the corresponding mass-loss rate.

To provide a comparison of how strongly the hot-Jupiter planets lose mass by stellar irradiation we also calculate mass loss estimates for solar system planets making the same assumptions as for the extrasolar planets; this implies in particular that they have a hypothetical atmosphere of gases with mainly H/He (which is clearly not the case for the inner solar system planets). In Fig. 5 we plot the thus derived maximal mass loss rates for our sample stars and those derived for the solar system gas giants. Fig. 5 indicates all our exoplanetary candidates have maximal mass-loss rates some orders of magnitude larger than the mass-loss rates of solar system gas giants; this is due to the fact that these planets are, first, orbiting much closer to their host stars, and second, that the intrinsic X-ray luminosity of the hosts is much larger than that of the present-day Sun.

Furthermore, we compare our four targets with two other well studied hot Jupiters HD 209458 b (Charbonneau et al. 1999) and HD 189733 b (Bouchy et al. 2005). HD 209458 b is an exoplanet with a mass of 0.69 M$_J$ and a radius of 1.38 R$_J$ orbiting a G2V star (46 pc away from the Sun) at a distance of 0.047 AU with a period of 3.52 days. The X-ray luminosity of HD 209458 has recently been measured by Chandra HRC as $L_X \sim 27.20$ erg s$^{-1}$ (Czesla et al. 2017), yielding an XUV luminosity of $L_{XUV} \sim 28.23$ erg s$^{-1}$; it also shows ongoing mass loss through hydrodynamic escape (Sanz-Forcada et al. 2010). HD 189733 b has a mass of 1.142 M$_J$ and radius 1.138 R$_J$ orbiting around a K1/K2 star HD 189733 (19 pc away from the Sun) orbiting at a distance of 0.03 AU with a period of about 22.2 days. The X-ray and XUV of luminosities of HD 189733 are $L_X \sim 28.18$ and log $L_{XUV} \sim 28.85$ erg s$^{-1}$, respectively (Poppenhaeger et al. 2013).

All our targets are as bright as HD 209458 and HD 189733 in the X-ray and XUV ranges, making the planets extremely susceptible to atmospheric mass loss. Using these XUV luminosities, the mass loss rate of HD 209458 b is calculated to be $9.3 \times 10^{10}$ gs$^{-1}$, consistent with the lower limit mass loss rate of $7.6 \times 10^{10}$ gs$^{-1}$ derived by Linsky et al. (2010). For HD 189733 b, the mass loss rate was estimated to be about $2.3 \times 10^{11}$ gs$^{-1}$ by Poppenhaeger et al. (2013), it is thus comparable to within an order of magnitude of the value obtained for Kepler-210c and Kepler-63b. In addition, we note that the mass loss rate of HD209458 b is comparable to the upper-limit mass loss rate of HAT-P-11b.
although the latter orbits further away from its host star. Also, the upper-limit mass loss rates of WASP-19 b and Kepler-210 b are at least an order of magnitude higher than those in the prototypical targets HD 209458 and HD 189733. Rather, the mass loss rate of these planets are comparable to CoRoT-2 b, which orbits around the extremely active planet host star with an X-ray luminosity of $2 \times 10^{39}$ erg/s (Schröter et al. 2011). The X-ray flux received by CoRoT-2 b is $\sim 9 \times 10^3$ erg cm$^{-2}$ s$^{-1}$, which corresponds to a formal mass loss rate of $4.5 \times 10^{-12}$ g s$^{-1}$. However, Salz et al. (2016b) show that CoRoT-2 is one of the most compact planets with very efficient radiative cooling, thus preventing the development of a strong wind. With the observations present here we have laid the groundwork for further detailed studies of these exoplanet hosts.

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