1. INTRODUCTION

X-ray emission has been observed for many of the solar system objects, e.g., for Mars (Holmström et al. 2001; Gunell et al. 2004; Dennerl 2002), Venus (Bhardwaj et al. 2007; Dennerl et al. 2002), Earth and the Moon (Collier et al. 2014; Bhardwaj et al. 2007), Jupiter and the Galilean satellites (Cravens et al. 2003; Bhardwaj et al. 2007), Saturn (Branduardi-Raymont et al. 2010), comets (Cravens 2002; Lisse et al. 2004), and in the heliosphere (Cravens et al. 2001).

For the solar system planets, X-rays are known to be generated via different mechanisms. The main mechanisms are as follows.

1. Continuum Bremsstrahlung emission due to collisions with electrons (produces mostly hard X-rays).
2. Excitation of neutral species and ions due to collisions, e.g., with electrons (charged particle impact), followed by line emission.
3. Stellar X-ray photon scattering from neutrals in planetary atmospheres (elastic scattering and K-shell fluorescent scattering, requires a significant column density).
4. Charge exchange between the solar wind ions with neutrals (Solar/Stellar Wind Charge Exchange Mechanism, SWCX), followed by X-ray emission.
5. X-ray production from the charge exchange of energetic (energies of about a MeV amu \(^{-1}\)) heavy ions of planetary magnetospheric origin with neutrals or by direct excitation of ions in collisions with neutrals (this is known to be effective on Jupiter, e.g., Cravens et al. 2003; Bhardwaj et al. 2007).

The cross sections at solar wind energies for charge exchange with the solar wind heavy ions are several magnitudes larger than the cross sections for the excitation of the neutral species by electrons (Bhardwaj et al. 2007), which makes the SWCX mechanism more effective.

In the present Letter, we discuss the SWCX mechanism and X-ray scattering as applied to close-in giant exoplanets, in particular to HD 209458b. We discuss the observability of the X-ray emission from HD 209458b, X-ray emission from other giant planets, and the influence of the host star age. Other X-ray production mechanisms are beyond the scope of the present Letter, but will be the goal of a future study.

2. SOLAR WIND CHARGE EXCHANGE MECHANISM

In the SWCX mechanism, an electron is transferred from a neutral atom or molecule to a highly charged heavy ion of the solar wind. This mechanism is known to produce soft X-rays in cometary comas (Cravens 2002). In the case of a magnetized planet, these ions can enter the neutral atmosphere following the open field lines near the polar cusp.

It is known from experimental and theoretical studies that solar wind heavy ions can undergo charge exchange reactions when they are within approximately 1 nm of a neutral atomic species (e.g., Lisse et al. 2004; Cravens 2002; Bhardwaj et al. 2007, and references therein):

\[
A^{q+} + B \rightarrow A^{(q-1)+} + B^*, \tag{1}
\]

where \(A\) is a charged heavy ion in the solar wind (the projectile), \(q\) is the projectile charge, and \(B\) is a neutral component (target). The product ion \(A^{(q-1)+}\) is still highly charged and is almost always left in an excited state (marked by an “\(^*\)”). Then, the excited ion emits one or several X-ray photons in the following reaction:

\[
A^{(q-1)+} \rightarrow A^{(q-1)+} + h\nu, \tag{2}
\]

Although the de-excitation usually represents a number of cascading processes through intermediate states, if \(q\) is high then an X-ray photon (at least one, though usually several) is emitted (Cravens 2002).
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The composition of the solar wind by volume is 0.92 hydrogen, 0.08 helium, and \( \approx 10^{-3} \) heavier elements. Since the solar wind quickly becomes collisionless as it expands, the charge states that the heavy ions have in the hot solar corona are frozen-in, and therefore the heavy elements are usually highly charged. In the solar wind, the most common heavy ions are \( \text{C}^{4+}, \text{C}^{5+}, \text{N}^{6+}, \text{O}^{6+}, \text{O}^{7+}, \text{O}^{8+}, \text{Ne}^{8+}, \text{Si}^{9+}, \text{Fe}^{12+} \).

The cross sections for such charge transfer collisions are very high at solar wind energies, exceeding \( 10^{15} \) cm\(^2\) (e.g., Greenwood et al. 2001). The types of the species that undergo charge exchange define the energy of the emitted X-ray photons, which is usually in the range of 0.3–0.5 keV.

### 3. SWCX MECHANISM ON HOT JUPITERS: THE CASE STUDY OF HD 209458B

In this section, we discuss the soft X-ray emission which can be produced by the SWCX mechanism on close-in exoplanets. As an example, we consider HD 209458b, which is a well-studied close-in gas giant orbiting a 4 ± 2 Gyr old G-type star. Planetary and stellar wind parameters are summarized in Table 1. In our further estimations, we rely on results of Kislyakova et al. (2014), who investigated the magnetosphere and stellar wind parameters in the vicinity of HD 209458b by means of modeling. Their result support a magnetic moment of HD 209458b of approximately 10% of the Jupiter’s and a stellar wind with a velocity of \( 4 \times 10^7 \) cm s\(^{-1}\) at the time of observation.

For a very simple estimate of the X-ray intensity, \( I \), emitted in the region of the atmosphere exposed to heavy ion precipitation one can use the following expression (Cravens et al. 2003):

\[
4\pi I \approx 2n_{sw}v_{sw}fN,
\]

where \( N \) is a factor of 2 or 3 and represents the number of photons emitted per ion (below we assume \( N = 3 \)). The additional factor of 2 on the right hand side is a flank magnetosheath enhancement factor (Cravens et al. 2003).

For Jupiter, Equation (3) yields \( 4\pi I \approx 10^5 \) cm\(^2\) s\(^{-1}\) while values of \( 2 \times 10^{16}–2 \times 10^{17} \) cm\(^2\) s\(^{-1}\) are necessary to explain the observed auroral soft X-ray emission, which means that SWCX is not the main mechanism that produces soft X-ray emission for Jupiter.

For HD 209458b, we assume the stellar wind parameters estimated by Kislyakova et al. (2014), \( n_{sw} = 5 \times 10^3 \) cm\(^{-3}\), \( v_{sw} = 4 \times 10^7 \) cm s\(^{-1}\) and \( f \approx 10^{-3} \) which gives \( 4\pi I \approx 1.2 \times 10^{17} \) cm\(^2\) s\(^{-1}\) or 60–600 times the observed Jovian values.

Given its proximity to its host star, it is unclear whether HD 209458b is located in the sub-Alfvénic or super-Alfvénic region of the wind. The exact regime depends on the magnetic moment of the host star and stellar wind parameters. Although the results of Kislyakova et al. (2014) support that HD 209458b is rather in the super-Alfvénic regime and thus outside the stellar plasma corotation region, we make an estimate also for the corotation case. HD 209458b has been observed to have a rotational velocity of 4.4 km s\(^{-1}\), which corresponds to a rotational period of \( \approx 11.5 \) days (Mazeh et al. 2000). This gives the corotational velocity of plasma at 0.047 AU of \( v_{sw} \approx 2.7 \times 10^6 \) cm s\(^{-1}\). Taking into account also the Keplerian orbital speed \( v_{obs} \approx 1.4 \times 10^7 \) cm s\(^{-1}\), this corresponds to the plasma flow velocity in the vicinity of HD 209458b of \( v_{flow} \approx 1.2 \times 10^7 \) cm s\(^{-1}\). Substituting it into the Equation (3) instead of \( v_{sw} \), one obtains an estimate of \( 4\pi I \approx 3.6 \times 10^{19} \) cm\(^2\) s\(^{-1}\), which is still 18–180 times the observed Jovian value.

To estimate the aurora size of HD 209458b, we follow the approach of Vidotto et al. (2011). The fractional area of the planetary surface that has open magnetic field lines is \( (1 - \cos a_0) \) for both the north and south auroral caps, where

\[
a_0 = \arcsin[(R_p/R_s)^{1/2}],
\]

\( R_p \) is the radius of a planet, and \( R_s \) is the magnetosphere stand off distance at the substellar point. Assuming \( R_s = 2.9R_p \) estimated by Kislyakova et al. (2014), we obtain \( a_0 \approx 0.63 \) and \( 1 - \cos a_0 \approx 0.19 \). This gives the size of the aurora of \( A \approx 2.17 \times 10^{20} \) cm\(^2\), or \( \approx 217 \) times the Jovian aurora \( A_J \approx 10^{18} \) cm\(^2\) (Cravens et al. 2003).

Now we can estimate the power of the soft X-ray emission from HD 209458b in both the corotation and non-corotation regimes. For simplicity, we assume the energy of each emitted X-ray photon is 0.3 keV (Cravens et al. 2003). Using the solar value of \( f = 10^{-3} \), we estimate the total X-ray power of HD 209458b to be \( \approx 1.3 \times 10^{20} \) erg s\(^{-1}\) in the non-corotation regime (point C on Figure 1) and \( \approx 2.3 \times 10^{19} \) erg s\(^{-1}\) in the corotational regime (Figure 1, point D).

Note that these values can still present a lower limit. If charge exchange occurs not only in the auroral regions of HD 209458b, but in the whole hemisphere with the radius of \( R_s \), the values should be multiplied by a factor of \( \approx 88 \), which is the ratio of the interaction area sizes. This gives \( \approx 1.1 \times 10^{22} \) erg s\(^{-1}\) in the non-corotation regime (point A in Figure 1) and \( \approx 2.0 \times 10^{21} \) erg s\(^{-1}\) in the corotation regime (Figure 1, point B). Since the atmospheres of hot Jupiters in general and HD 209458b in particular are highly inflated and are believed to extend beyond the magnetosphere (Kislyakova et al. 2014), this is a more realistic case than interaction only in the aurora region (Jupiter type). The X-ray production can be even larger if the region outside the magnetosphere (the volume between the magnetopause and the bow shock) is included (Robertson & Cravens 2003).

#### 3.1. Contribution of Stellar X-Ray Photon Scattering

Although only a small fraction of the incident stellar X-rays are reflected by the planetary atmosphere, in the solar system this mechanism is known to contribute to the total soft X-ray luminosity of planets and dominates, for example, the X-rays from Venus (Dennerl et al. 2002). Cravens et al. (2006) showed that the scattering albedo for the outer planets is quite small and equals \( 10^{-3} \) at 3 nm. We assume this albedo for HD 209458b as a crude estimate.

The total X-ray luminosity of HD 209458 was first observed to be \( \log L_X \approx 27.02 \pm 0.2 \) erg s\(^{-1}\) (Kashyap et al. 2008).

| Name                          | Valuea            |
|-------------------------------|-------------------|
| Planetary mass, \( M_p \)     | \( \approx 0.71 \) \( M_J \) |
| Planetary radius, \( R_p \)   | \( \approx 1.38 \) \( R_J \) |
| Semi-major axis               | \( \approx 0.047 \) AU |
| Stellar wind velocity, \( v_{sw} \) | \( 4 \times 10^7 \) cm s\(^{-1}\) |
| Stellar wind density, \( n_{sw} \) | \( 5 \times 10^4 \) cm\(^{-3}\) |
| Fraction of heavy ions \( f \) | \( 10^{-3} \) |
| Planetary magnetic moment, \( M_p \) | \( \approx 0.1 \) \( M_J \) |
| Magnetospheric stand-off distance, \( R_s \) | \( 2.9 \) \( R_p \) |

Notes.  
\(^a\) Adopted from Kislyakova et al. (2014).  
\(^b\) Solar wind value assumed.
The slight difference in the stellar X-ray flux with that given by Kashyap et al. (2008) is due to the use of a different distance.

The planetary X-ray emission could be observed using the secondary transit, as commonly done in the infrared, for example. The ratio between the in-transit and out-of-transit fluxes is expected to be of the order of $10^{-5}$ erg cm$^{-2}$ s$^{-1}$, which would require a signal-to-noise ratio (S/N) of the measurements of the order of $10^5$ to be detected. Such a high precision is currently reached in the optical and infrared bands (mostly with space observations), but it is prohibitive at X-ray wavelengths. To highlight this, we used the available count rate simulator\(^7\) for the XMM-Newton telescope that, among the facilities currently available, has the largest efficiency in the soft X-rays. Taking into account the 0.1–1.0 keV band, a plasma with a temperature of $10^6$ K, and the count rate given for the pn detector and the “thin” filter we obtained a count rate of $3.9 \times 10^{-3}$ count s$^{-1}$ for the X-ray emission of HD 209458. As a result, the S/N obtained exposing for $10^3$ s is about 2 and it would require several thousand years of exposure time to reach the S/N required to detect the planetary X-ray emission. The situation might slightly improve if the planetary X-ray emission has a different spectral behavior compared to that of the star, but the detectability would probably remain unfeasible. Here we have not considered the intrinsic stellar X-ray variability which will hamper the detection of the planetary X-ray emission.

5. SWCX MECHANISM ON OTHER GIANT EXOPLANETS

In this section, we briefly consider the influence of the orbital distance on the soft X-ray emission generated by the SWCX mechanism (the radius of HD 209458b is assumed). For the stellar wind parameters, we consider two cases: for one case, we assume the wind has the properties of the slow component of the current solar wind, and for the other case, we scale the wind properties to match what we might expect for the young solar analogue EK Dra.

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\(^7\) http://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
We calculate the solar slow wind parameters as a function of distance from the star using a one-dimensional hydrodynamic wind model that is constrained by in situ spacecraft measurements of the real solar wind. The model was developed by Johnstone et al. (2015b) and provides a very good description of the real solar wind outside of the solar corona.

Although little is known about the properties of winds from other stars, it is suspected that more active stars have mass fluxes that are significantly higher than the mass flux of the current solar wind (Wood et al. 2005; Holzwarth & Jardine 2007; Suzuki et al. 2013). To scale the slow solar wind model to EK Dra, we use the scaling relation for mass loss rate derived by Johnstone et al. (2015a) and the parameters for EK Dra given by Güdel (2007).

We find a mass-loss rate and therefore corresponding values for \( n_{sw} v_{sw} \) for EK Dra that are approximately a factor of 15 higher than in the current solar wind.

Based on the example of the solar wind, we might expect that the abundances of heavy ions are similar in the corona and in the wind. While it is known that the coronal abundances are correlated with coronal activity for Sun-like stars, the coronal abundances of the most active stars are only approximately a factor of two different from the solar values (Telleschi et al. 2005). Since this is an insignificant difference compared to all other uncertainties, for simplicity we assume a solar value of \( f \approx 10^{-3} \).

Magnetic moments of tidally locked gas giants are believed to be smaller than \( M_\text{J} \) because of their slower rotation (Grießmeier et al. 2004; Khodachenko et al. 2012). For HD 209458b, this hypothesis was lately also supported by a modeling result based on the Lyo transit observations (Kislyakova et al. 2014), which predicted a planetary magnetic moment of \( M_\rho \approx 0.1 M_\text{J} \). Although a prediction of magnetic moments of hot Jupiters \( M_\rho \geq M_\text{J} \) also exists (Christensen et al. 2009), in the present study we assume a moment value in the range of \( \approx 0.05–0.5 M_\text{J} \) (see Figure 2 in Khodachenko et al. 2012).

The size of the aurora is calculated according to Equation (4) and the magnetopause stand off distance following the relation (Baumjohann & Treumann 1996)

\[
R_s = \left( \frac{\mu_0 f_0 f_\rho M_\text{J}^2}{2\pi^2 \rho_{sw} v_{sw}} \right)^{1/6},
\]

(5)

where \( \mu_0 \) is the diamagnetic permeability of free space, \( f_0 \approx 1.22 \) is magnetosphere form-factor.

Figure 1 presents the dependence of the emitted soft X-ray power on the orbital distance of the planet. The letters mark the emission levels for HD 209458b estimated above. We should note that we did not take into account the unknown rotation rate of the host star, which leads to an overestimate of the plasma flow speed and, respectively, the emission level in the corotation regime. The letter marks for HD 209458b do not lie exactly on the lines because of the difference between simple estimates used for \( R_s \) and \( M_\rho \) to those estimated via comprehensive modeling by Kislyakova et al. (2014). As a consequence, these plots only qualitatively describe the behavior of the soft X-ray emission due to the SWCX mechanism. For every particular planet, an individual consideration should be made similar to the one above for HD 209458b.

The main conclusion of our results is that the soft X-ray emission is the highest for closest hot Jupiters and strongly depends on the interaction area size (see the difference between the aurora and the whole hemisphere case—lower and upper red and blue lines, respectively). The simple Equation (4) (Vidotto et al. 2011) can be used only for hot Jupiters and yields a significant overestimate for Jupiter (see the two green lines). For non-tidally locked gas giants on wide orbits, the lower green line presents the most plausible estimate.

We should also note that the corotation regime probably breaks closer to the star than shown on Figure 1. However, this is not so easy to restrict because of many unknown parameters.

Soft X-ray emission from exoplanets orbiting a younger star with a denser stellar wind is always stronger than the emission from an planet embedded in the current solar wind (Equation (3)), which is confirmed by Figure 1(b), simply because the number of emitted photons is proportional to the wind mass flux assuming the same \( f \).

6. CONCLUSIONS

In this work, we presented a simple estimate of the possible X-ray emission from the close-in gas giants emitted due to the SWCX mechanism. We have shown for the example of HD 209458b that this mechanism alone can be responsible for the X-ray emission intensity of the order of \( \approx 10^{22} \) erg s\(^{-1} \), which is \( \approx 10^6 \) times higher than the X-ray emission from Jupiter.

We have discussed the possibility of observing the soft X-ray flux from close-in extrasolar giant planets and have shown that although this emission exceeds the intensity of the Jovian soft X-ray emission by several orders of magnitude, it is unobservable with present-day facilities because of the large distances to the systems.

The main conclusion of the study is that hot Jupiters should be bright X-ray sources in comparison to the solar system giant planets. The spectrum of this emission as well as the influence of other X-ray producing mechanisms should be the subject of future study.

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