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Planet erosion by coronal radiation

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Abstract

According to theory, high energy emission from the coronae of cool stars can severely erode the atmosphere of orbiting planets. To test the long term effects of the erosion we study a large sample of planet-hosting stars observed in X-rays. The results reveal that massive planets ($M_{\rm p} \sin i > 1.5$ $M_{\rm J}$) may survive only if exposed to low accumulated coronal radiation. The planet HD 209458 b might have lost more than 1 $M_{\rm J}$ already, and other cases, like τ Boo b, could be losing mass at a rate of $3.4\,M_\oplus$/Gyr. The strongest erosive effects would take place during the first stages of the stellar life, when the faster rotation generates more energetic coronal radiation. The planets with higher density seem to resist better the radiation effects, as foreseen by models. Current models need to be improved to explain the observed distribution of planetary masses with the coronal radiation received.

1 Introduction

The discovery of exoplanets has reached a point in which it is possible to study more detailed properties of planets, such as mass evolution. Once the planet is formed, and the original disc is dissipated, the main agent interacting with the atmosphere should be the high energy emission from the corona of the star, for late type stars. The photons with $\lambda < 912$ Å can ionize hydrogen atoms, assumed to be the main component of the atmosphere of giant planets. The effects of X-rays ($\lambda\lambda$1–100) and Extreme Ultraviolet (EUV, $\lambda\lambda$100–912) photons take place at different heights in the atmosphere of the planet. While EUV photons mainly ionize the atoms in the upper atmosphere, the X-rays penetrate deeper in the atmosphere.

The free electrons produce a cascade of collisions while the X-rays photons are absorbed in the atmosphere [2]. These collisions heat the atmosphere resulting in its "inflation" and eventually the evaporation of a part of it. The gravity of the planet acts as a protection, trying to keep the atmosphere attached to the planet. If we assume that the planet atmosphere is mainly composed by hydrogen, and all the photons in the whole XUV range (X-rays + EUV) are absorbed and contribute to the heating of the atmosphere, it is possible to calculate the mass loss of the atmosphere by balancing the losses with the planet gravity [14, 5]. An additional source of mass losses takes place through the Roche Lobe for close-in planets [3] included in the formula through the variable K ($K \leq 1$). Some authors consider that evaporation actually takes place at a point somewhere above the planet radius ($R_{\rm p}$), at the "expansion radius" (R_1) [1]. The resulting formula [11] is:

$$\dot{M} = \frac{4\pi\beta^3 R_{\rm p}^3 F_{\rm XUV}}{{\rm G}KM_{\rm p}}, \tag{1}$$

where $\beta = R_1/R_{\rm p}$, $F_{\rm XUV}$ is the X-ray and EUV flux at the planet orbit, and G is the gravitational constant. Although some heat may be absorbed at R_1, most XUV flux should be absorbed below $R_{\rm p}$, where most of the atmosphere is enclosed. Thus we can safely assume $\beta \simeq 1$. The formula can be simplified using the mean density of the planet (ρ), and assume that $K \simeq 1$ (valid for most cases):

$$\dot{M} = \frac{3F_{\rm XUV}}{{\rm G}\rho}\,. \tag{2}$$

Stars with spectral types ranging from mid-F to early-M have stellar coronae with temperatures of $\sim$1 MK, exceeding 10 MK in the most active cases. The high temperature material in the transition region ($\sim \log T$ = 4–5.8) and corona ($\sim \log T$ = 5.8–7.4) emits copious X-rays and EUV flux. Fast rotators have a hotter corona, resulting in a higher XUV flux. Since the younger stars have a faster rotation, the XUV emission of the late type stars decreases with time. The evolution of X-rays emission with age has been studied for the Sun (e.g. [6, 9]) and extended to G and M stars [8, 7]. A relation using late F to early M stars has been calibrated by [4] in the X-rays band, allowing us to calculate the age of the stars from its X-rays emission, and to trace the time evolution of this emission. Current instruments allow only access to the X-rays band, but there is little information on the EUV emission in stars other than the Sun, limited to $\lambda\lambda$100–400 for the best cases due to the absorption of the radiation in the interstellar medium.

The distribution of planet masses with current emission from the coronae of the stars should reflect the accumulated effects of the mass loss in the atmospheres of the planet over time. Besides, if we know the evolution of the emission in the whole XUV band we should be able to trace the planet evolution, given an accurate knowledge of the density of the planet, according to Eq. 2. We carry out a program to observe the X-rays emission of stars with exoplanets and evaluate these and other effects. We have developed a database ("X-exoplanets", http://sdc.cab.inta-csic.es/xexoplanets/jsp/exoplanetsform.jsp,) that includes not only observations of the stars in X-rays, but also synthetic spectra in the EUV range [10], available through the Spanish Virtual Observatory (SVO). We analyzed X-rays data awarded

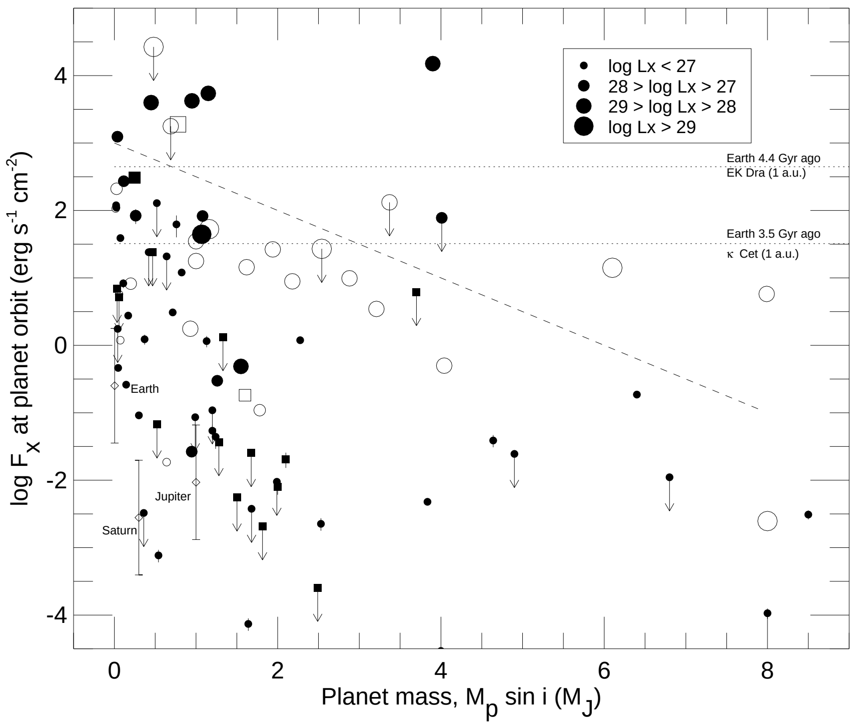

Figure 1: Distribution of planetary masses ($M_{\mathrm{p}} \sin i$) with X-ray flux at the planet orbit. Filled symbols (squares for subgiants, circles for dwarfs) are XMM-Newton and Chandra data. Arrows indicate upper limits. Open symbols are ROSAT data without error bars. Diamonds represent Jupiter, Saturn, and the Earth. The dashed line marks the "erosion line". Dotted lines indicate the X-ray flux of the younger Sun at 1 a.u. Adapted from [11].

to us, including an XMM-Newton Large Observation (proposals #02065304, #02000001, #05510229), and archival XMM-Newton and Chandra data. The scientific results [11, 12] are outlined in next section.

2 Results

Direct XUV observational data of stars with exoplanets can be acquired only in the X-rays band with present instruments. Since X-rays and EUV are formed in the same region and temperatures, the trends observed in X-rays should be extrapolative to the whole XUV range. We have calculated the X-rays flux by fitting the spectra of all the stars with exoplanets observed with XMM-Newton or Chandra, and complemented these data with ROSAT observations with S/N > 3. A total of 101 planets in 88 stars are included in the sample. We can interpret the results keeping in mind Eq. 2. The distribution of F_{XUV} with masses (Fig. 1) reveal a clear separation that seems to be related to mass[1]. We plotted a line ("erosion line") that roughly follows this separation. This line is not based on any previous assumption or physical law. The Solar System planets are included for comparison, with vertical segments indicating the variations over the solar cycle. We also include the radiation level arriving at the Earth when the life appeared, 3.5 Gya, and when the Sun had an age of only 1 Gyr. We used the solar young analogs [9] κ^1 Cet and EK Dra to mimic the flux at the Earth's orbit in the past. Figure 1 can be interpreted in the same manner as the HR diagram: the absence of planets in a given area of the diagram implies that they spend little time in that stage. In this sense the distribution seems to indicate that the planets suffer heavy erosion in the first stages until they are below the "erosion line", when either the stellar XUV flux decreases and/or the gravity of the planet protects the planet from mass loss, slowing down the erosion. Planets positioned initially at further distances will not suffer substantial mass loss. We can also divide the diagram in four quadrants based on the mass (at 1.5 M_J) and the X-ray flux at the planet orbit (at $\log F_X = 2.15$). Only 1 out of 12 of the planets receiving high flux have high mass, while 46 out of 89 (a 52%) of the planets receiving lower fluxes have a high mass. Therefore it is clear the absence of high mass planets suffering high flux levels.

To test the effects over time we have also used the dependence of X-rays emission with time. We need also the EUV evolution with time, but the only estimates made to date are valid just for the Sun [9], and a relation applicable to all late type stars is necessary. The first step needed is to calculate the EUV flux. The process is rather complex and it is better explained in [10, 12]. We use the spectral information in X-rays to derive a coronal model, extrapolate the model to the transition region if no UV lines are available[2], and predict the spectral energy distribution in the whole EUV range using the atomic model APED [13]. We have derived a relation between X-rays and EUV luminosity ($L_{\rm EUV} \sim L_{\rm X}^{2.65}$) that we use to calculate the EUV flux of the stars with ROSAT data. We also calculated the age of the stars using their X-rays luminosity, and constructed a relation in the EUV range with the best data of our sample ($\log L_{\rm EUV} \simeq 29.22 - 1.41 \log \tau$, where τ is the age in Gyr). Figure 2 shows the accumulated flux at the orbit of the planet, considering the time between an age of 20 Myr and the present. The observed distribution with mass would be a direct indication of the mass lost by the planets since an age of 20 Myr, assuming that all mass losses are included in Eq. 2, and the density is the same for all planets. The distribution shows that only three planets with $M_{\rm p} > 1.5$ M_J have survived an XUV flux of more than 10^{21} erg cm^{-2}: for two of them there are alternative explanations [11] and the third, τ Boo b, is a young object that might still be suffering heavy erosion.

The second important variable in Eq. 2 is the planet mean density. A more dense planet is better protected against evaporation. Ideally our analysis should concentrate on stars with known L_X and planets with known density. Only four planets have both magnitudes known, and one of them, 2M1207 b is too far from the star to suffer mass losses. Instead we can test the whole population of planets with known density, a total of 103 planets. Most of these planets have been detected trough the transits technique, therefore having a strong

[1]Planets orbiting giants and cataclysmic variables were excluded from the analysis.

[2]The model of the temperature structure in the transition region is typically calculated from UV lines, formed at lower temperatures than those in X-rays.

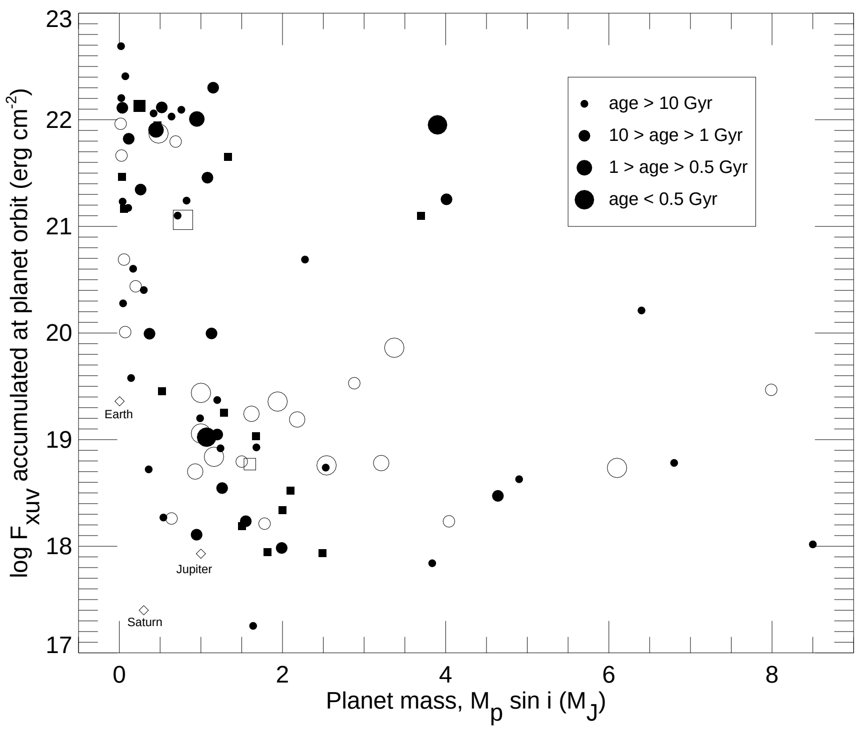

Figure 2: Distribution of planetary masses ($M_{\rm p} \sin i$) with the X-ray flux accumulated at the planet orbit since an age of 20 Myr to the present (see text). Symbols as in Fig. 1.

bias towards close-in planets, those more exposed to high XUV flux. We do not find massive planets with small density among this population (Fig. 3). This might indicate that low density planets with high mass have suffered a quick erosion taking them to the population with jovian masses, or increasing their density because of the lower atmosphere-to-nucleus ratio. Finally we have made a calculation of the mass evolution for the mentioned three planets with known density and $L_{\rm X}$, including the calculated $L_{\rm EUV}$, according to Eq. 2, and including in this case the mass losses through the Roche Lobe expressed in Eq. 1. Figure 3 shows this evolution assuming that density has been roughly constant over time and no other effects toke place. The case of HD 209458 b is remarkable, with more than 1 $M_{\rm J}$ lost to date. This work has considered only a rather simple model with the thermal losses in the atmosphere, but non-thermal losses should be included in the future, together with other smaller effects that may be necessary to explain the distribution observed in Fig. 1.

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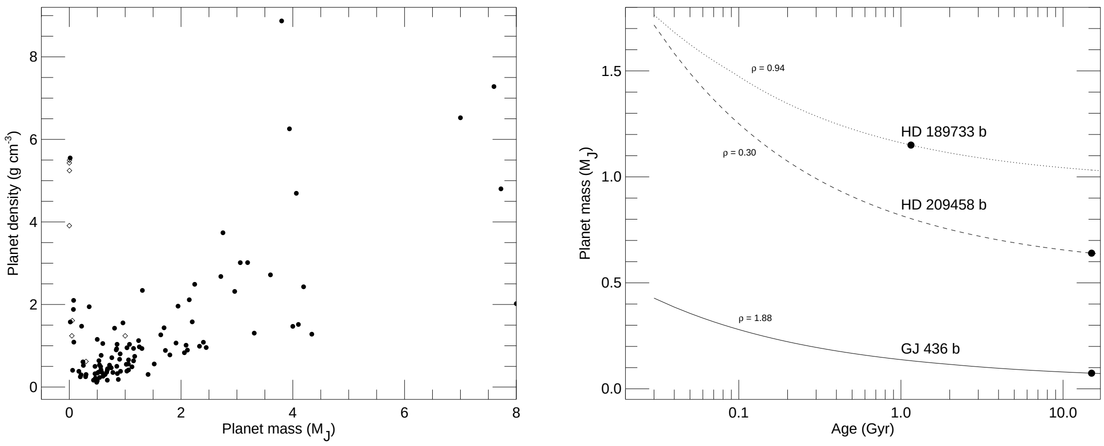

Figure 3: *Left*: Density of the 103 planets of known radius (17 Nov 2010) with $M_{\rm p} < 8\,{\rm M_J}$ (filled circles). Diamonds represent the Solar System planets. *Right*: Planetary mass evolution as an effect of the XUV radiation. Mass losses include evaporation by coronal radiation and losses through the Roche Lobe. Planet mean density is indicated, as well as the current stellar age of the planet, calculated using the X-ray luminosity (see text).

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