Future Exoplanet Research: XUV (EUV and X-ray) Detection and Characterization

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Abstract This chapter gives an overview of the current status of XUV research in exoplanets and highlights the prospects of future observations. Fundamental questions about the formation and the physical and chemical evolution of exoplanets, particularly hot Jupiters, are addressed through the different lines of XUV research: these comprise XUV irradiation of planetary atmospheres by the host stars, and consequent mass loss and atmospheric evaporation; X-ray and UV transits in exoplanet systems; and Star-Planet Interactions, most often determined by magnetic and tidal forces. While no other UV instrumentation as powerful as that carried by the Hubble Space Telescope will be available for detailed studies in the foreseeable future, the discovery potential of future revolutionary X-ray observatories, such as ATHENA and Lynx, will provide accurate atmosphere characterization and will make strides towards establishing the physics of the interactions between exoplanets and their host stars.

Introduction

The majority of observations of exoplanets to date have been dedicated to obtaining accurate time series measurements for photometric transit studies and radial velocity measurements in the optical bandpass while the atmospheres of a handful of hot Jupiters have been studied spectroscopically in the infrared and UV bands, and radio studies are underway to search for the possible signatures of exoplanet magnetospheres.

The XUV band (1 – 912 Å, or approximately 12 keV – 10 eV) separates in energy into EUV (Extreme UV, 10 – 100 eV) and X-ray (0.1 – 12 keV). These two energy regimes offer an alternative view of exoplanets, and one that is becoming increasingly important since it has been realised that high energy radiation is likely to play a key role in the formation and early evolution of planetary systems. For example, Glassgold et al (1997a, 1997b) describe the creation of a layered circumstellar disk under X-ray irradiation, where the quiescent conditions in its deeper layer would favour the formation of planets. A serious observational drawback, however, is represented by our inability to detect cosmic EUV emissions because of the intervening interstellar absorption. Hence in order to estimate the hidden EUV stellar flux (and its effects on exoplanet atmospheres) coronal models are used. In the absence of EUV flux data, these models are often constrained by UV line measurements below the EUV band and by X-ray measurements above it.

Most of the exoplanet systems we know of are associated with cool stars with convective outer atmospheres (spectral types F, G, K, M), which are known to be magnetically active to various degrees and produce enhanced emissions in the UV and X-ray bands. Stellar rotation is the most significant parameter in driving the X-ray output, and since rotation rates decline with age, the dependence of X-ray characteristics on rotation turns into dependence on the star's age. Activity is most commonly observed in the form of X-ray flares that can surpass the power produced in solar flares by up to five orders of magnitude (up to 10^{37} erg). Planets orbiting these hosts, especially hot Jupiters occupying close-in (0.02 – 0.1 AU) orbits, are frequently subject to irradiation which can be variable in extreme ways and reach levels of flux more than five orders of magnitude larger than that received from the Sun by the Earth (e.g. 8.5×10^4 erg cm^{-2} s^{-1} for CoRot-2, Schmitt 2017).

Photometric observations of planetary transits have been mainly carried out in the optical and UV bands where host star activity is not much of a hindrance and good signal to noise ratio can be achieved. Especially in the more marginal cases and where particularly active host stars are involved, flaring activity can contaminate the X-ray light curves, introduce planet unrelated variability and reduce our ability to detect transit signatures. Hence an effective 'cleaning' of stellar flares from the X-ray light curves is the major obstacle to be overcome. Recently, observations with Chandra and XMM-Newton have been used to attempt detecting transit signatures in the X-rays, and one system, HD 189733, has emerged as a primary candidate (more on this in the next section).

Another unique aspect of the close relationship between exoplanets and their host stars is the so-called Star-Planet Interaction (SPI). Episodes of enhanced and periodic stellar activity taking place in systems harbouring planets have been reported, but only a couple of them have stood careful examination and testing; such kind of behaviour is reminiscent of the fact that stars are generally more active, in particular in X-rays, when belonging to binary systems rather than as single stars of the same type. The activity is normally attributed to magnetic or tidal exoplanet interactions (Cuntz et al 2000).

The following sections provide a summary of what we have learnt of the characteristics of exoplanets in high energy regime and of what we can look forward to learning in the near and more distant future, as new observing facilities come into operation.

What we have learnt so far

High energy (XUV) observations of exoplanet systems, confined to rely on space instrumentation by the absorption of the Earth's atmosphere, have become feasible only in this century, following the launch of sensitive X-ray observatories such as Chandra and XMM-Newton right at the end of the last century (although Swift has also been used to support studies of planet-related stellar variability). In the UV band only the Hubble Space Telescope (HST) instrumentation is available for exoplanet observing. Different strands of research have developed, addressing different aspects of the study of exoplanets and their properties, as outlined in the Introduction. In the following we consider what we have learnt of the effects of XUV irradiation on a number of exoplanet atmospheres, of the characteristics of exoplanetary transits in the UV and X-ray bands, and of the signatures of Star-Planet Interactions (SPI) which are thought to be generated by magnetic and tidal forces acting between the planets and their host stars.

XUV irradiation and evaporation

XUV illumination has a powerful impact on the physical and chemical evolution of planetary atmospheres and exospheres by ionising and dissociating molecules, so that light elements can escape into the interplanetary medium. Even if the planet possesses a magnetic field, XUV irradiation may expand its atmosphere beyond the magnetosphere, making it subject to erosion (Lammer et al 2011). Penz et al (2008) looked at the influence of the evolving X-ray luminosity distribution of G stars on the population of close-in hydrogen-rich planets and found that a third of them may completely evaporate away in 4 Gyr, with the remaining planet mass distribution shifted to smaller masses. A study of the distribution of exoplanet masses in the presence of X-ray irradiation by Sanz-Forcada et al (2010) indeed supports the idea that planet atmospheres have been eroded by their host star coronal emissions. Further, Jackson et al (2012) study the evolution of the X-ray emission with stellar age and apply it to investigating the evaporation history of 121 transiting exoplanets, providing estimates of the fraction of mass lost since their formation. Sanz-Forcada et al (2014) have also explored the special case of circumbinary planets where the fast rotation rate of close, tidally-locked binary host stars leads to a copious XUV irradiation that can be very efficient at evaporating the planets. This may explain the paucity of observations of planets with short orbital periods in circumbinary systems.

In extreme cases intense XUV irradiation is likely to lead to hydrodynamic blow-off of (some of) the atmosphere of a planet, especially if in close-in orbit around the host star. Lammer et al (2003) carried out the first proper computations of the loss rates ($\sim 10^{12}$ g s^{-1}) from exoplanets under XUV illumination, which are found to be in agreement with values measured from spectrally resolved Lyα planetary transits (e.g. HD 209458b, Vidal-Madjar et al 2003). These mass loss rates could be even higher for young solar-type host stars and could also explain the small number of exoplanets discovered at orbital distances < 0.04 AU. Many estimates of mass loss rates have been obtained with the HST Cosmic Origins Spectrograph (COS), the UV channel of the HST Advanced Camera for Surveys (ACS) and the Space Telescope Imaging Spectrograph (STIS) (e.g. Linsky et al 2010 for HD209458b; Lecavelier des Etangs et al 2010, 2012 and Bourrier et al 2013 for HD 189733b, where significant variability in the planetary atmosphere conditions was also found). Salz et al (2016) have recently simulated the escaping atmospheres of gas planets in the solar neighbourhood, deriving improved estimates of planetary mass loss rates, and estimates of Lyα absorption and emission in the two cases of compact small cool planets and massive hot ones, where they dominate respectively. The general behaviour of escaping planetary atmospheres they computed is illustrated in Fig. 1, where density, temperature, velocity and specific heating rate are plotted versus distance from the planet, for two exoplanet systems, HD209458 and HD189733. Interestingly the simulation shows that a significant amount of planetary atmosphere gas can be located at a distance of a few planetary radii from what could be taken as the planet's surface.

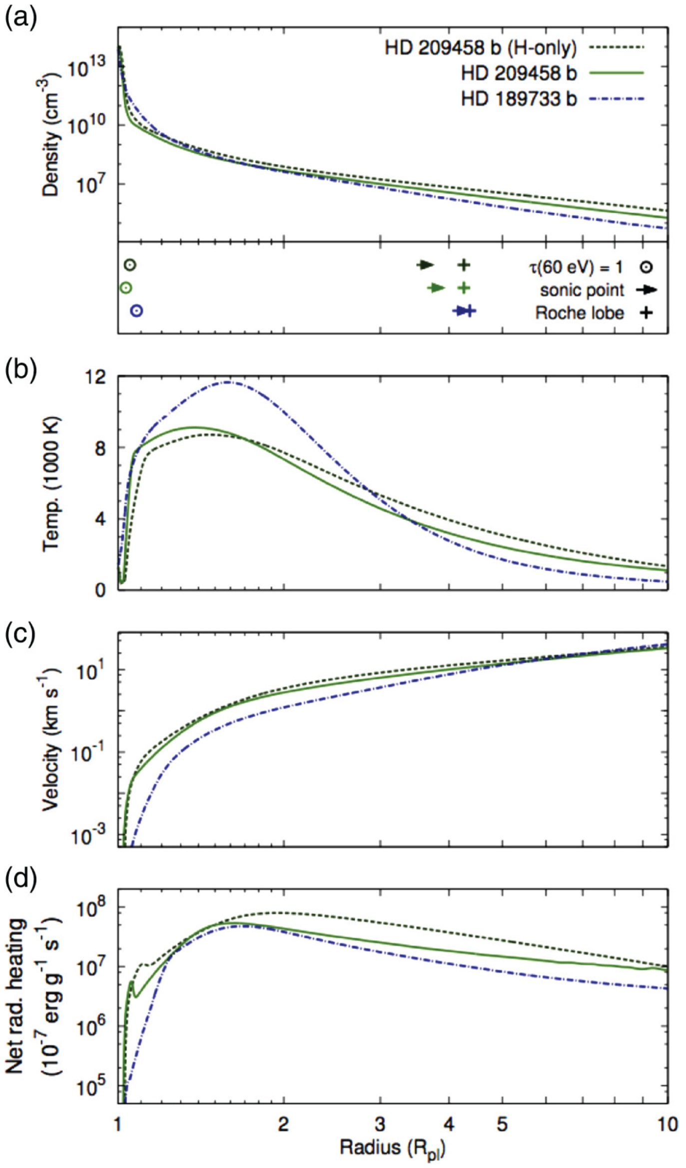

Fig. 1 Outer atmospheres of HD 209458b and HD 189733b. For HD 209458b, both a hydrogen-only and a hydrogen and helium simulation are shown, with the run of density, temperature, velocity, and the specific heating rate plotted. The symbols in the lower panel (a) indicate the τ (60 eV) =1 levels (circles), the sonic points (arrows), and the Roche lobe heights (plus signs), with the order of the planets according to the legend. Figure and caption from Salz et al (2016).

A major hindrance towards correctly quantifying the planet atmospheric evaporation and the ionization of the outflow is the lack of measurements of the EUV flux, which is absorbed and hidden by interstellar absorption. Louden et al (2017) have developed a procedure in order to model the missing part of the spectrum using a Differential Emission Measure retrieval technique, which is constrained on one side by the UV line strengths measured by HST COS and on the other by XMM-Newton measurements. Applying this technique to HD209458b results in an ionising luminosity of ~10^{28} erg s^{-1}, which leads to a mass loss rate that is up to a factor of 10 higher than that derived from UV transit spectroscopy. This could be due to having ignored the effect of variability in previous works. In any case the knowledge of the whole spectral energy distribution is instrumental to a correct modeling of the evaporation of planetary atmospheres.

CoRoT-2 is an exceptional system where a very active host star has a possible late type stellar companion and the transiting hot Jupiter has one of the largest radii observed. A Chandra X-ray observation and optical spectroscopy with the VLT UV Echelle Spectrograph (UVES) confirm that the companion star (unseen in the X-rays) is gravitationally bound to the host star and that the planet is illuminated by an intense flux of high energy radiation (Schroter et al 2011). The X-ray light curve of the host does not show any sign of variability and appears to be simply quiescent emission. Furthermore there is no evidence of any planetary X-ray transit. It is speculated that the presence of the host star companion may have had an impact on the evolution of the system and may be related to the anomalous radius of the planet and its eccentric orbit.

An example of Neptune-mass exoplanet with an escaping atmosphere is provided by GJ 436b (Ehrenreich et al 2015), where the mass loss signature is taken to be the deeper and longer transits observed in UV compared to the optical ones. HST STIS Lyα spectroscopy shows deep absorption only in the blue wing of the line as the planet moves from pre-transit to in-transit to post-transit (see Fig. 2). The velocity range of the absorption exceeds the planet's escape velocity, so it is consistent with gas escaping from it. Numerical simulations lead to a model for GJ 436b involving a comet-like tail that causes the absorption of Lyα blue wing when it moves across the line of sight relative to Earth (Fig. 3).

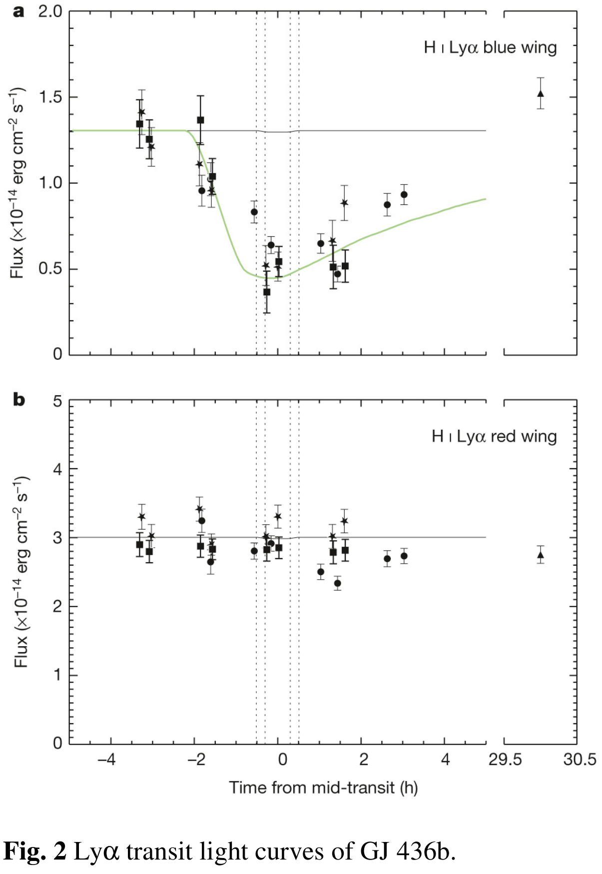

Fig. 2 Lyα transit light curves of GJ 436b.

a The Lyα line blue wing shows absorption signals with respect to the out-of-transit flux of 17.6% (pre-transit), 56.2% (in-transit) and 47.2% (post-transit). The different data markers correspond to four HST observations spread over four years.

b The line red wing shows no notable absorption signals. With a depth of 0.69%, the optical transit (thin black lines in **a** and **b**) is barely seen at this scale between its contact points (dotted lines in a and b). A synthetic light curve (green) calculated from a 3D numerical simulation is overplotted on the data in **a**. Figure from Ehrenreich et al (2015).

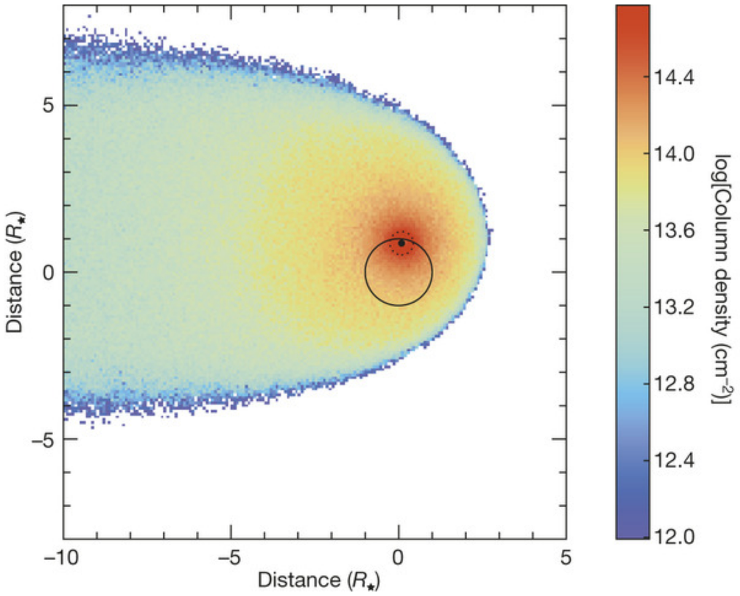

Fig. 3 Particle simulation showing the comet-like exospheric cloud transiting the star, as seen from Earth. GJ 436b is the small black dot shown at mid-transit at $0.8521R_\star$ from the centre of the star, which is represented by the largest black circle. The dotted circle around the planet represents its equivalent Roche radius. The colour of simulation particles denotes the logarithm of the column density of the cloud. The transit of this simulated cloud gives rise to absorption over the blue wing of the Lyman-α line as shown spectrally and by the synthetic light curve in Fig. 2. Figure and caption from Ehrenreich et al (2015).

Chandra observations contemporaneous with STIS spectroscopy of GJ 436b allow an estimate to be made of the EUV flux illuminating the planet, which is in good agreement with what can be derived from the Lyα measurements. The average mass escape of 5×10^8 g s^{-1} from GJ 436b requires a ~1% efficiency in the XUV energy flux conversion to mass loss. Much higher irradiation energy in the past could have led the planet to lose a large fraction of its atmosphere (~10%) during the first billion years of its evolution.

The determination of the XUV flux driving mass loss is a major source of uncertainty in modeling exoplanet atmospheres evaporation and has been the subject of detailed theoretical studies (e.g. Chadney et al 2015). HD 97658b makes an interesting 'control experiment' with respect to GJ 436b, being a moderately irradiated super-Earth (Bourrier et al 2017a). No absorption signatures are observed in the Lyα line from the parent star, which as a weak soft X-ray source will subject HD 97658b to a level of irradiation three times lower than GJ 436b. This suggests that detection of atmospheric mass loss is not biased by the methodology adopted.

A very different case of planetary response to XUV irradiation is provided by TRAPPIST-1, a very cool system incorporating a dwarf host star and seven Earth-size planets, of which three are expected to be temperate. Despite the low Lyα emission of the host star relative to its X-ray flux (Wheatley et al 2017), the XUV irradiation is much larger than that operating on Earth and is deemed to be sufficient to strip the atmospheres of the planets in a few billion years (Bourrier et al 2017b). The exceptional characteristics of this system make it an important laboratory for future study and modeling of exoplanet atmospheric evolution.

The recent discovery of a terrestrial planet candidate in a temperate zone orbiting Proxima Cen (Anglada-Escude et al 2016) sharply raises the fundamental question of habitability, at least in terms of presence of an atmosphere and surface water. An accurate characterization of the irradiation environment of Proxima b (Ribas et al 2017) shows that the XUV irradiance on the planet is nearly 60 times that on Earth. This, together with proposed new laws of the XUV flux evolution over time, will help interpreting future observations of this remarkable system, with many inferences for Earth and our solar system too.

Although the majority of the exoplanets discussed so far are associated with cool stars, there are a few examples (six at the latest count) of planets transiting hot (7000 – 10,000 K) A-type stars: their discovery is probably hampered by the host's fast rotation and paucity of spectral lines, making Doppler tomography challenging; the consequence is a still poor understanding of their physical structures and properties. The latest systems to join this sample are KELT-9 and KELT-20 (also known as MASCARA-2) which have been discovered as part of the Kilodegree Extremely Little Telescope all-sky survey. KELT-9 (Gaudi et al 2017) incorporates a very hot (~ 10,000 K) fast spinning A-type star with a transiting planet in a 1.48 day orbit at 0.03 AU, heated to a temperature of ~ 4000 K by the very strong irradiation from the host. This is in itself the kind of temperature of a K star with large thermal emission, and analysis of the secondary eclipse suggests that the dayside of the planet may be even hotter. Under the huge EUV flux (see Fig. 4) the photochemistry of the planet's atmosphere must be very unusual, and opacity be dominated by atomic metals rather than molecules. The estimated mass loss rate of about $10^{10} – 10^{13}$ g s^{-1} could lead to the planet being stripped of most of its envelope during the host's main-sequence phase. KELT-20 (Lund et al 2017) was simultaneously discovered by Talens et al (2017) who named it MASCARA-2, as they used the Multi-site All-Sky CAmeRA (MASCARA), specifically designed to find the brightest transiting planetary systems in the sky ($m_V < 8.4$). Both sets of authors concur on an effective temperature of just under 9000 K for the host A-type star, and an equilibrium temperature of ~2200 K for the transiting planet. Unlike what is typically found for planets orbiting hot early-type stars, KELT-20b orbit normal is aligned with the host star spin axis. A second MASCARA observing facility is expected to start operations at the European Southern Observatory at La Silla, Chile, in the summer of 2017, which will lead to more discoveries of this relatively scarce planet population in the southern hemisphere.

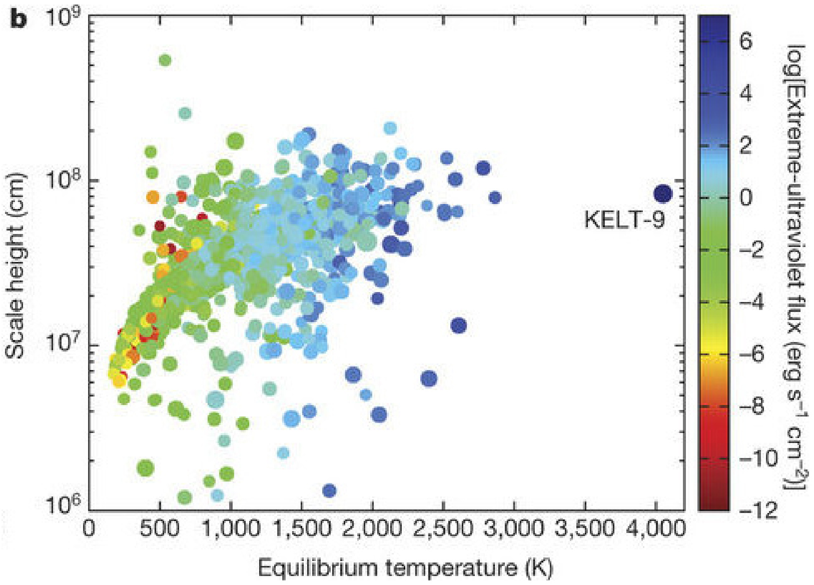

Fig. 4 Atmospheric scale height vs equilibrium temperature for known transiting planets with measured masses. Colour represents the incident EUV ($\lambda \leq 91.2$ nm) flux on the planet from its parent star, and the symbol size is inversely proportional to the V magnitude of the host. KELT-9b is hotter than any other known transiting gas giant planet and receives about 700 times more EUV flux. Figure and caption from Gaudi et al (2017).

Finally, it is worth noting that the system HD 189733, discussed in terms of both X-ray transits and SPI in the next sections, plays a role also in the context of XUV atmosphere irradiation and evaporation: this follows from the suggestion that evaporated material from the planet could accrete onto the host star leading to X-ray enhancements after egress from secondary eclipse (Pillitteri et al 2015).

X-ray transits

Fig. 1 clearly suggests that the size of a planet, as derived from the transit depth and duration, at XUV wavelengths can be larger than that in the optical band. An extreme example of this in the UV is the already mentioned exoplanet system GJ 436b (Ehrenreich et al 2015) which displays a 56% transit depth and a 6 hr transit duration in the UV compared to less than 1% depth and 1 hr duration in optical.

Of the thousands of exoplanets known by now only one, HD 189733b, has potentially been observed producing an X-ray transit. The system consists of an active K-type star with one of the closest (at 0.03 AU) hot Jupiter transiting planets and an M-type stellar companion. From their Chandra observing campaign Poppenhaeger at al (2013) select data when the star was in quiescence and obtain an X-ray transit detection at 99% confidence (Fig. 5). The fact that the X-ray transit is deeper (6-8%) than the optical one (2.4%) is indicative of the presence of an extended atmosphere opaque to X-rays but transparent to optical wavelengths. However the risk remains that the observations covered a non typical part of the corona, hence further transit observations will be necessary to definitively confirm this result. Indeed Marin and Grosso (2017) on the basis of Monte-Carlo radiative transfer simulations of HD 189733 predict a transit depth of ~ 2% in the 0.25 – 2 keV range and also argue that current X-ray facilities cannot detect the very small signal expected from reprocessing of the host star emission in the planetary atmosphere.

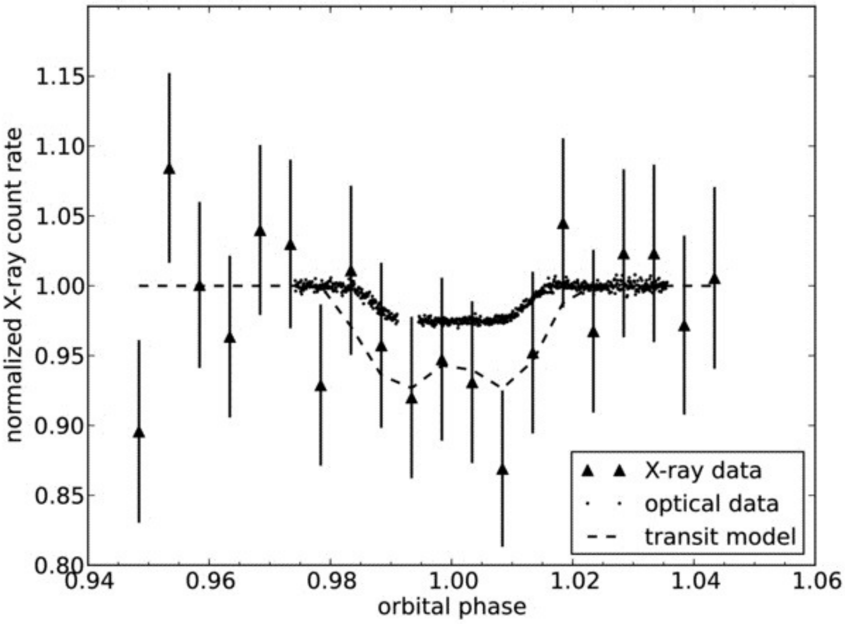

Fig. 5 Chandra X-ray transit data from quiescence periods of HD 189733b superposed on the optical transit observed by Winn et al (2007). The dashed line shows the best fit to a limb-brightened transit model from Schlawin et al (2010). Figure and caption from Poppenhaeger et al (2013).

Star-Planet Interaction (SPI)

Evidence for magnetic or tidal interaction of exoplanets, normally hot Jupiters, with their host stars can be gathered from cyclical episodes of enhanced stellar activity occurring in synchrony with the planet's orbital period. Magnetic interaction at small star-planet separation can indeed lead to X-ray enhancements according to the MHD simulations of Cohen et al. (2009). Hence the ability to detect these signatures crucially depends on our knowledge of the host star's intrinsic activity and how this evolves with time. This kind of search was first carried out in the optical (e.g. Shkolnik et al 2008) using chromospheric activity indicators such as the variability of the Ca II H λ3968, K λ3933 lines.

The first systematic study of X-ray coronal activity of giant planet host stars by Kashyap et al (2008) was based on archival and targeted observations by the major X-ray telescopes since the Einstein Observatory. After taking into account possible biases the authors concluded that stars with close-in (< 0.15 AU) giant planets are on average more X-ray active than those systems where planets are further away (> 1.5 AU) from the host stars. However, a subsequent statistical analysis by Poppenhaeger et al (2010) of all the exoplanet systems known at the time within 30 pc indicated that, while in a few individual systems coronal SPI may cause enhanced X-ray emission, this does not apply in general when considering the full sample, and no correlation with planet parameters such as mass or semi-major axis was found. In another attempt to investigate the possible influence of close-in hot Jupiters on their host stars Poppenhaeger et al (2011) monitored the ν Andromedae system at both X-ray and optical wavelengths in order to study coronal and chromospheric behaviours, and only found a low level of stellar activity and no evidence of SPI.

Following another report of correlation between the X-ray emission of planet host stars and the mass of giant close-in planets based on archival ROSAT data (Scharf 2010), Poppenhaeger and Schmitt (2011) reanalyzed the sample taking into account its sensitivity limit and the bias introduced by planet detections via radial velocity methods, concluding that there is lack of evidence for significant influence of planets on their host stars X-ray activity. The correlation is also missing when considering a complete sample constructed by combining XMM-Newton and ROSAT data. More recently Miller et al (2015) have again used a combination of new and archival Chandra, XMM-Newton and ROSAT observations to test whether stars hosting hot Jupiters are systematically more X-ray luminous than those hosting smaller and more distant planets. No correlation was found. However, for a sample of 198 FGK main sequence stars they determined that the X-ray luminosity does appear to be related to planet mass and distance, and attributed this to a handful of extremely massive and close-in hot Jupiters whose hot stars are very X-ray luminous, although not unreasonably so compared to their chromospheric activity. Cumulative effects of tidal interaction between host stars and planets are thought to lead to stellar spin-up and eventual planet infall and destruction.

Interestingly, a similar approach was also taken by Shkolnik (2013) who investigated stellar activity with Near and Far UV observations made by the Galaxy Evolution Explorer (GALEX) of 272 FGK host stars and found no correlation between activity indicators and planetary parameters. However, in agreement with the mentioned X-ray and chromospheric results, also in this case there is some evidence that stars with close-in planets are more Far UV active than those with more distant planets.

One of the ‘special’ cases where SPI may be at work and observable is represented by the HD 189733 system already highlighted. Pillitteri et al (2010) reported XMM-Newton observations obtained in 2009 showing a softening of the X-ray spectrum during a secondary eclipse and enhanced activity in the form of a giant X-ray flare about an hour after the eclipse exit. Their relatively simple MHD model can reproduce satisfactorily the global characteristics of the observations suggesting that the stellar magnetic field could drag planet evaporated material into a density enhanced trail orbiting with the planet (Fig. 6) which could give origin to transient activity via magnetic reconnection.

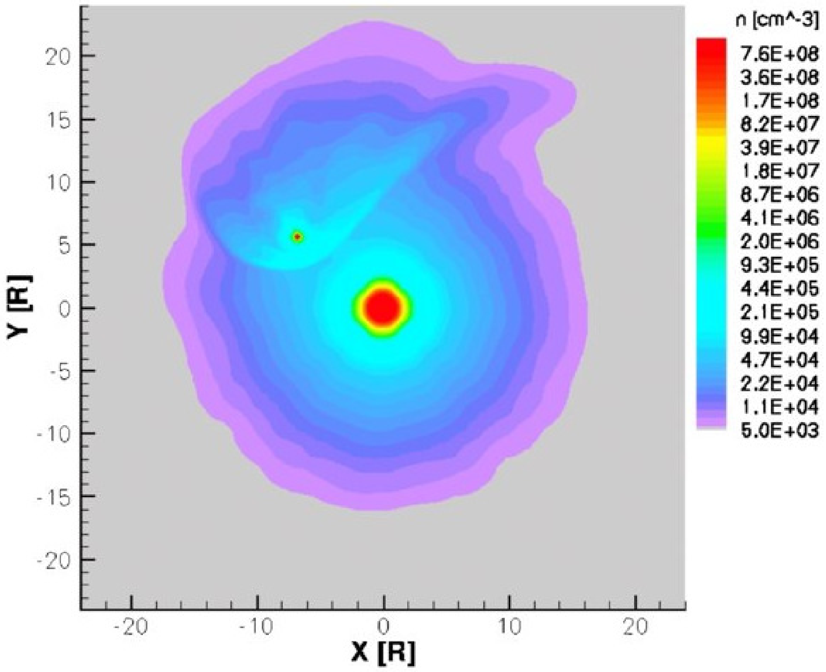

Fig. 6 Model prediction for the mass density distribution in the exoplanet system HD 189733. Figure from Pillitteri et al (2010).

A flaring event at the same orbital phase and with similar characteristics was observed again with XMM-Newton in 2011, and this led Pillitteri et al (2011) to postulate that systematic SPI is taking place when the orbiting planet passes near its host star active regions. For a third time a large X-ray flare was observed after secondary eclipse in 2012 with XMM-Newton (see Fig. 7). With all the flaring events being restricted to the phase range 0.55 – 0.65, Pillitteri et al (2014a) again argue that the planet may trigger the flares when passing near a region of high magnetic field on the host star. However, statistically they do not detect an excess of flaring activity at those phases when considering all XMM-Newton, Chandra and Swift observations of HD 189733 to date (Fig. 8).

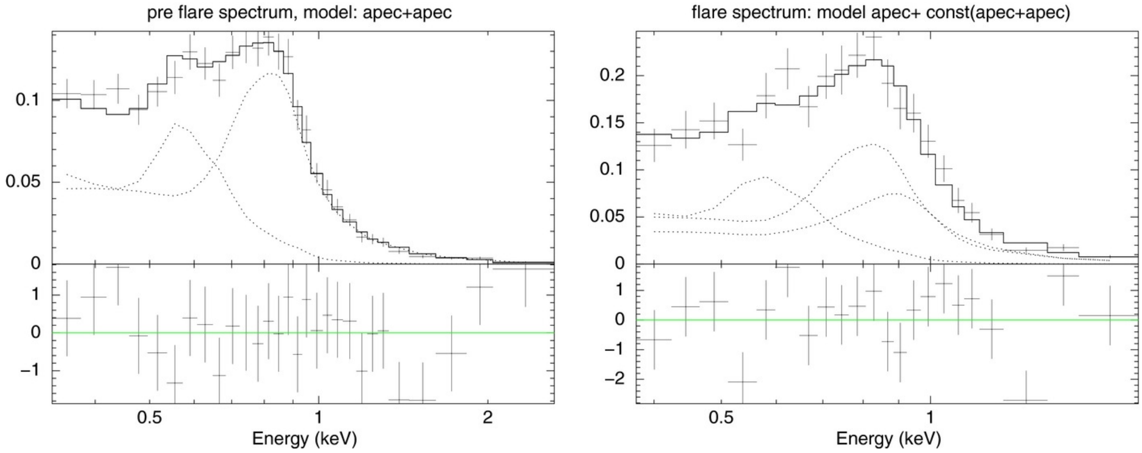

Fig. 7 XMM-Newton EPIC-pn spectra before the flare (left panel) and during the main flare (right panel) observed in HD 189733 in 2012. Dotted lines show the single thermal coronal components adopted for the best-fit spectral model. Figure from Pillitteri et al (2014a).

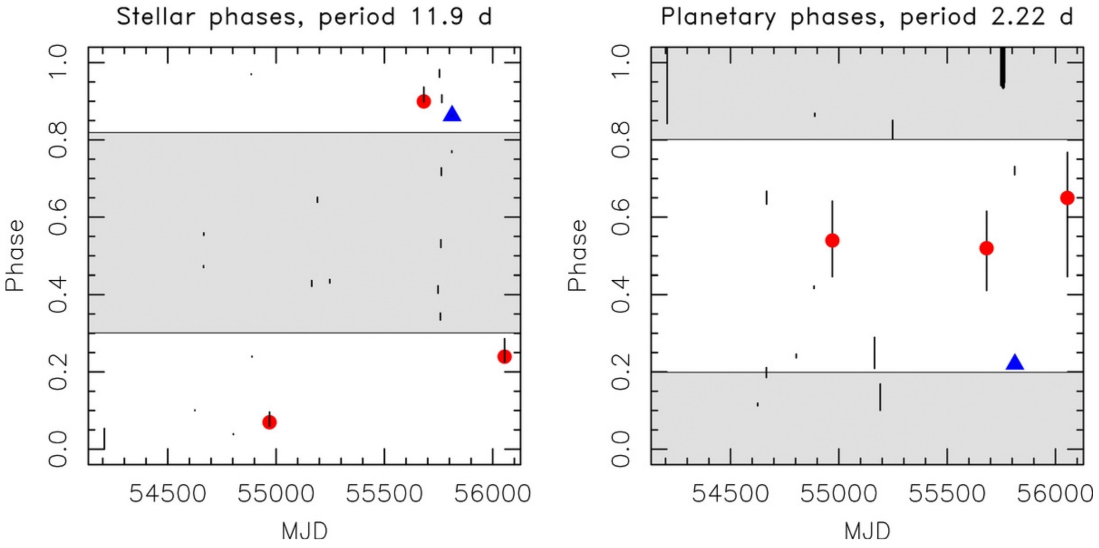

Fig. 8 Stellar rotational phases (left panel) and planetary orbital phases (right panel) during the X-ray observations obtained with XMM-Newton, Chandra, and Swift. Observations with intense flares are marked with filled symbols: red circles for XMM-Newton, blue triangles for Swift. In both panels, shaded areas mark the phase intervals without observations of large flares. Figure and caption from Pillitteri et al (2014a).

Evaporated material from the planet may also accrete onto the host star in HD 189733 and act as an additional mechanism producing X-rays: evidence for this comes from HST COS Far UV observations (Pillitteri et al 2015) which showed emission line variability occurring just after egress from secondary eclipse, at the same phase as the X-ray enhancements. MHD simulations demonstrate that material can effectively escape from the planet, become supersonic and impact on the host star, creating an active stream of dense and hot plasma linking the planet to the star.

Another interesting case is that of HD 17156, a system incorporating a hot Jupiter in a very eccentric orbit (Maggio et al 2015). XMM-Newton observations as the planet approached apoastron and then at periastron show the star is detected only at periastron (Fig. 9), when also chromospheric activity, as measured by simultaneous optical spectroscopy, was found to be enhanced. Such behaviour could be a consequence of magnetic reconnection and flaring, or alternatively accretion onto the host star of material stripped from the planet by tidal forces.

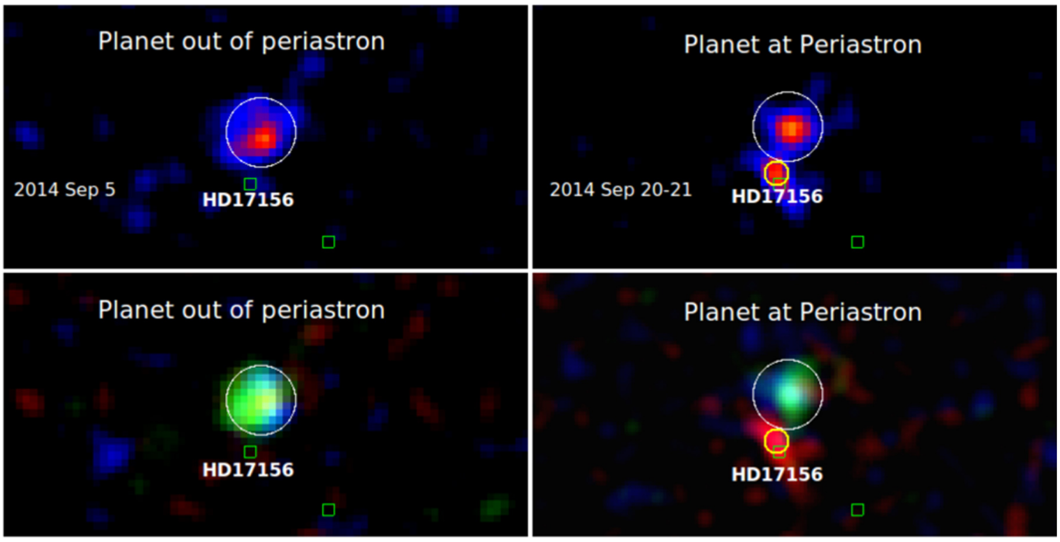

Fig. 9 X-ray images of HD 17156 away from planetary periastron (left) and near periastron (right) where HD17156 is clearly detected. Top: Intensity images. Bottom: False colour images with Red = 0.3-1 keV, Green = 2-2.5 keV, Blue = 2.5-5 keV. Circle sizes indicate the scales of HD 17156 and of an unrelated background object (the brightest in the field) with a harder spectrum. Figure and caption from Maggio et al (2015).

Because of the notorious difficulty in separating intrinsic stellar activity from planet driven X-ray flux enhancements (which lead to a bias in favour of low activity host stars and small mass exoplanets) Poppenhaeger and Wolk (2014) took a different approach: they selected wide binary stellar systems where one component has an orbiting planet and the other has not, so that they could use coronal X-ray activity as indicator of magnetic activity that could then be associated with the presence of the planet. Indeed, in two systems where significant tidal interactions could be expected the stars with an orbiting planet showed stronger X-ray activity, while in three systems where a lower degree of interaction was expected the stars displayed similar levels of coronal X-ray emission to their binary companions. The authors conclude that hot Jupiters may well have an impact on their host stars and inhibit their spin down, by angular momentum transfer, or influence the early evolution of the system when the star may have decoupled from its protoplanetary disk where formation of the hot Jupiter created a physical gap.

A sort of ‘reverse case’ of SPI may be presented by WASP-18, an F6-type star with a hot Jupiter orbiting it in less than 20 hours and a star-planet separation of 0.02 AU. The remarkable closeness of the two bodies suggests that this is a configuration where SPI may be at work through tidal and magnetic processes. Unexpectedly the star is undetected in a deep Chandra exposure, with an X-ray luminosity upper limit (4.5×10^{26} erg s^{-1}) which is two orders of magnitude below what is expected for a star of its age (600 Myr) and mass (Pillitteri et al 2014b). The lack of X-ray activity is consistent with the low chromospheric activity which also characterizes the star, and indicates a lack of magnetic dynamo efficiency. In this case it is argued that it may be tidal influence of the giant planet that determines the character of the host star structure and activity (or rather lack of it).

A view of the future

As long as they remain operational, currently available X-ray observing facilities such as Chandra and XMM-Newton can offer repeated and longer exposures on exoplanet targets; in combination with UV observations this can benefit irradiation and evaporation studies, and SPI searches. As current missions (e.g. Kepler, Gaia) and new facilities for exoplanet searches and characterisation at longer wavelengths (such as TESS, CHEOPS, PLATO) come into operation, thousands of new systems are expected to be discovered, some of them brighter than those known today and with orbital parameters (e.g. eccentricity) particularly favourable to further detailed studies with Chandra and XMM-Newton.

However, major breakthroughs in the XUV band probably will have to wait for drastically more sensitive X-ray observatories which are forthcoming in the next decades. Only a quantum step improvement in X-ray collecting area can match the challenge of reaching a sufficient signal to noise ratio on the very low X-ray fluxes expected, and the tough requirement of extracting SPI induced signatures of variability from that intrinsic to late-type stellar coronae. This quantum step (more than an order of magnitude larger X-ray collecting area) will be offered by the ATHENA (Advanced Telescope for High ENergy Astrophysics) observatory which is under development by the European Space Agency and is due for launch in 2028 (http://www.the-athena-x-ray-observatory.eu/). ATHENA should be joined in space by NASA's even more ambitious candidate mission Lynx (https://wwwastro.msfc.nasa.gov/lynx/) in the longer term (launch may be in the 2030s) combining possibly even larger collecting area with a spatial resolution aimed to match that of Chandra.

Plans are already in place to include in the ATHENA observing programme the most interesting exoplanet systems discovered to date, aiming to detect signatures of both, X-ray transits and SPI (Branduardi-Raymont et al 2013). The currently best candidate for SPI investigations with ATHENA, HD 189733b, is predicted to generate a reprocessed soft X-ray flux three to five orders of magnitude fainter than its primary star and less than 1×10^{-16} erg cm^{-2} s^{-1} at most before ingress and after egress (Marin and Grosso 2017). In this context, a similar result can also be obtained by a simple scaling of Jupiter's disk X-ray flux, which is due to reprocessing of solar illumination, to the conditions of HD 189733b: using the observed Jovian disk and solar X-ray luminosities at minimum and maximum in the solar cycle (e.g. Branduardi-Raymont et al 2010, Fig. 5) and scaling to the shorter host-planet distance and cooler and smaller star in the HD 189733 system, the ratio between stellar and planet X-ray luminosities is two or four orders of magnitude respectively. Modulation of the X-ray flux with orbital phase in the HD 189733 system may just be detectable in very long observations with ATHENA (sensitivity limit of ~ 10^{-17} erg cm^{-2} s^{-1}). The ATHENA observing programme clearly will need to evolve according to the discoveries brought about by new observational facilities at longer wavelengths, as already touched upon. Repeated spectroscopic observations of X-ray transits at high signal to noise ratio, and comparison of X-ray transit depth and characteristics with those at longer wavelengths, will allow constraining models of atmospheric composition, evaporation and eventually exoplanetary evolution. Higher temporal resolution made possible by the larger photon flux collected by ATHENA will result in better 'cleaning' of the contamination induced by the host star intrinsic variability. ATHENA's vast collecting area will permit the extension of the study of magnetic and tidal SPI signatures to a larger range of interesting targets that are currently below the sensitivity limits of the available observing facilities.

X-ray observations with ATHENA will provide additional insights in the environment and physical conditions of exoplanets also in other respects. As an example, Kislyakova et al (2015) suggested that the process of charge exchange (CX) could take place between heavy ions in the host stellar wind and neutral atom clouds around planets, leading to X-ray emission (similar to what happens at comets in our solar system, and at Mars, Venus and Earth as the planets' atmospheres and magnetospheres respond to the dynamic impact of the solar wind). Calculations of the expected fluxes, though, predict far too low levels compared with Chandra and XMM-Newton sensitivity limits. On the other hand, the recently reported (and controversial) detection of X-rays from Pluto (Lisse et al 2017) has been attributed to charge exchange between the solar wind, in some way significantly focused and enhanced in the vicinity of the dwarf planet, and neutral gas escaping from it. This would suggest that the odds are not all against making similar detections for exoplanets. Again, in the intervening time to ATHENA (and Lynx) brighter systems may be discovered where stellar wind CX may eventually be detectable. In term of numbers of stellar systems likely to contain exoplanets and accessible to these X-ray studies, Branduardi-Raymont et al (2013) note that about half of the > 100,000 sources detected in the ROSAT All Sky Survey (which will be bright sources for ATHENA) are stars of spectral type F – G and at least 14,000 of them are optically brighter than V ~ 11.5 in the Tycho catalogue.

Speculating further about what the (distant) future may bring, we can consider the prospects of detecting exoplanets through analysis of X-ray timing anomalies in 'cosmic clocks'. In fact the first ever exoplanet detection was achieved by examining the irregularities in the radio pulse period of the millisecond pulsar (MSP) PSR B1257+12 (Wolszczan and Frail 1992). To date only three exoplanet systems hosted by MSPs are known, with their rarity being attributed to their formation process (Martin et al 2016). However, since MSPs are generally emitters from the radio to the X-ray band, it can be argued that in future we may be able to apply the same type of anomaly analysis to X-ray timing measurements of MSPs, and extend them to X-ray binary pulsators, where accretion is the mechanism powering the X-ray emission. Similarly, with significant improvements in X-ray sensitivity, transit timing variations (TTV) could be investigated, eventually leading to reveal new planets and moons.

Spaceborne UV observatories planned or being considered for the foreseeable future, such as WSO-UV (World Space Observatory-UV, Russian led, due for launch in 2022, with half the collecting area of HST, http://www.wso-uv.es/) and ARAGO (proposed in response to the ESA M5 opportunity set for a launch in 2030, http://arago-mission.obspm.fr/) will not offer even comparable performance to HST. However, the Large UV-Optical-IR Surveyor (LUVOIR, https://asd.gsfc.nasa.gov/luvoir/) concept mission, selected by NASA to be studied in preparation of the 2020 Decadal Survey, would enable the in-depth study and characterization of a wide range of exoplanets over the band 90 – 400 nm: its remarkably large mirror (8 – 16 m aperture – 10 to 40 times the geometric collecting area of HST) and wavefront stability would provide exceptional spatial resolution and high contrast coronagraphy for exoplanet direct imaging. While in the near future UV observations must rely on HST continuing operations for as long as possible, Fossati et al (2015) argue about the importance of building a large HST data archive of exoplanet UV transit observations for atmospheric characterization, targeting systems accurately selected on the basis of their host star, planet and orbital properties, in particular considering the systems that will be discovered in the near future by missions such as TESS, CHEOPS and PLATO.

Conclusions

The future of exoplanet research is bright, more and more systems are discovered every day, and this rate will accelerate with the new space missions, operating in the visible band, under development and close to launch, such as TESS, CHEOPS and PLATO. Detailed investigations of planetary atmospheres and Star-Planet Interactions rely heavily on UV and X-ray observations, the latter being particularly challenging because of the faint planetary signatures which have to be identified against the host star coronal emission and variability. Much more powerful X-ray facilities than presently available are going to be deployed starting at the end of the next decade (ATHENA due for launch in 2028, Lynx possibly flying in the 2030s). These promise a quantum leap in discovery potential for exoplanet science, allowing also much scope for serendipitous discoveries that are always brought about by instrumental advances. In the UV, while preparing for possible future missions today still at the concept level, we must make the most of the capabilities of HST and create an archive of strategically targeted observations which will constitute an unparalleled legacy for the foreseeable future.

Cross-references

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