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Title: X-ray views of our solar system

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Abstract

The solar system comprises a relatively small number of X-ray emitting objects, which are associated with a variety of physical emission processes: we can explore them with good spatial and temporal precision at relatively local distances, and in situ as well, unlike the rest of the Universe. Moreover, from the study of the solar system we can gather insights into extra-solar planets too. This article offers a review of our current knowledge of the X-ray properties of bodies in our solar system, of the physical processes leading to X-ray emissions, and of recent breakthrough discoveries brought about by space probes providing remote imaging as well as in situ measurements. In the long term, the next generation of Earth bound X-ray observatories and the possibility of in situ X-ray measurements, i.e. by X-ray telescopes onboard spacecraft visiting the planets, will underpin the next giant leap in discovery space.

Keywords: emission processes; planets; solar system; X-rays

Abbreviations:

ACIS, Advanced CCD Imaging Spectrometer; **CME**, coronal mass ejection; **CX**, charge exchange; **EPIC**, European Photon Imaging Camera; **JEDI**, Jupiter Energetic particle Detector Instrument; **HRC**, High Resolution Camera; **QP**, quasi periodic; **RGS**, Reflection Grating

Spectrometer; **SMILE**, Solar wind Magnetosphere Ionosphere Link Explorer; **STIS**, Space Telescope Imaging Spectrograph; **ULF**, Ultra Low Frequency; **UVS**, UV imager/Spectrograph

1 INTRODUCTION

This paper provides a review of the many observations and in depth studies that have been carried out on the X-ray emissions of solar system bodies. While the first observation and detection of Jupiter in the X-rays was made with the Einstein Observatory more than four decades ago (Metzger et al. 1983), the last twenty years have seen a remarkable progress in our understanding of the energetic physical processes taking place in planetary environments. Recent advances have also opened many new questions that we will try and answer with the next generation of Earth bound X-ray observatories and space probes measuring in situ at the planets.

2 WHAT WE HAVE DISCOVERED AND LEARNT SO FAR

2.1 X-ray astronomy workhorses since 1999

First of all, we have to give massive credit to XMM-Newton and Chandra: they have been for the past two decades, are now and hopefully will continue to be for many years, the workhorses of X-ray astronomy. These great X-ray observatories have allowed gigantic advances in our understanding of the Universe, and of solar system bodies in particular. Over the years we have come to realise how absolutely complementary the two facilities are. On the one side, Chandra (Figure 1 left, Weisskopf et al. 2000) provides exquisite spatial resolution by imaging with the High Resolution Camera (HRC, Zombeck et al. 1995) and the Advanced CCD Imaging Spectrometer (ACIS, Garmire et al. 2003), and spectral capability with both ACIS on its own, and coupling gratings to the imagers. On the other, XMM-Newton (Figure 1 right, Jansen et al. 2001) offers very large collecting area, CCD spectroscopy with the European Photon Imaging Camera (EPIC, Strüder et al. 2001, Turner et al. 2001) and, simultaneously, high resolution spectroscopy with the Reflection Grating Spectrometer (RGS, den Herder et al. 2001).

Figure 1. Artist impressions of the Chandra (left) and XMM-Newton (right) observatories (Image credit: NASA and ESA respectively)

The two observatories have combined to yield exceptional discoveries in all aspects of astronomy, and particularly by probing solar system objects in a variety of aspects, e.g. the objects' interactions with the solar wind; the global magnetospheric and auroral dynamics; mass and energy transport; planetary atmospheres; planet and satellite surface composition. All of these have led to spectacular advances, and have sparked new questions!

In the future (2030s) we will have Athena, ESA's next generation X-ray observatory (Nandra et al. 2013). Athena's combination of vast effective area and non-dispersive high spectral resolution (with the X-ray Integral Field Unit) will enable a new scientific revolution! And Athena will deploy its great potential for exoplanet studies as well, investigating in detail X-ray transits of exoplanets and host star-planet interactions.

2.2 X-ray emission mechanisms in the solar system: Jupiter

Firstly it is helpful to give a brief reminder of Jupiter's characteristics, considering that this planet has relevance to exoplanets too, such as hot Jupiters and warm Neptunes. Jupiter is a giant planet, with 10 times the radius of the Earth, a 10 hr rotation period, and possessing a magnetic moment 20,000 times that of Earth. Its gigantic magnetosphere, the cavity created in the solar wind by the planet's magnetic field, can extend past the orbit of Saturn. A cartoon highlighting the main elements of Jupiter's magnetosphere and a comparison with that of Earth is shown in Figure 2.

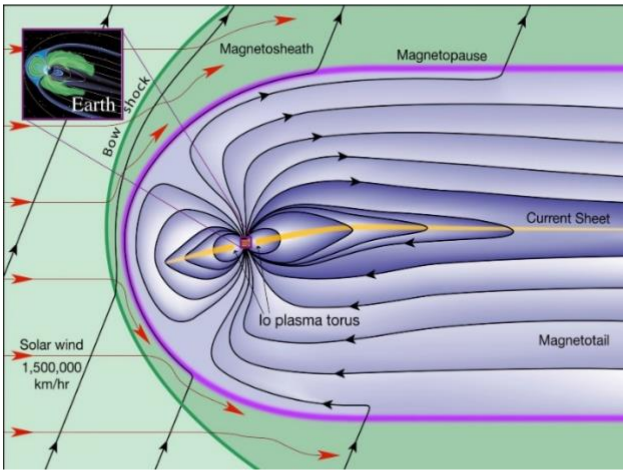
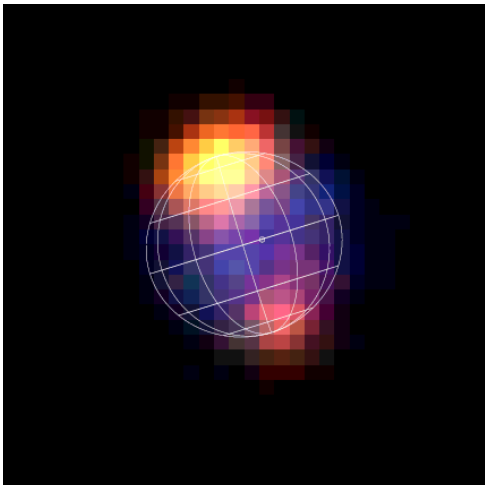


Figure 2. Comparison of Jupiter's and Earth's magnetospheres (from Bagenal 2007)

Jupiter exhibits most of the processes that produce X-rays in the solar system, starting with ionic charge exchange (CX), where a high charge ion acquires an electron from a neutral atom or molecule, is left excited and decays with the release of a characteristic emission line. CX was known as a source of X-rays since the dawn of atomic physics, but was first recognised as acting in the solar system with the X-ray detection of a comet over 20 years ago (Lisse et al. 1996), and now is known to be ubiquitous in the Universe.

Two other processes leading to X-ray production are at work on Jupiter. One is the scattering, elastic and fluorescent, of solar X-rays by H_2 and methane molecules in the upper atmosphere of the planet. This emission from the disk (Figure 3, left) is controlled by the Sun and varies in concert with the solar X-ray output (Bhardwaj et al. 2005a). Its spectrum is typical of optically thin emission, like that of the solar corona (Figure 3 right) (Branduardi-Raymont et al. 2007a).



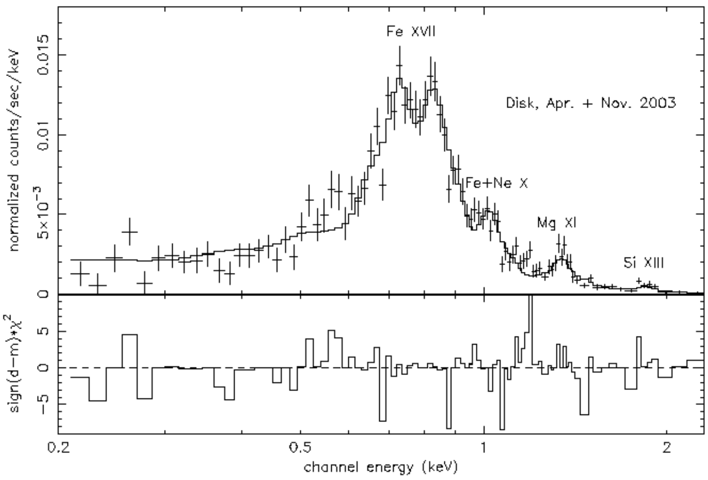


Figure 3. Left: XMM-Newton EPIC image of Jupiter (0.2 – 2.0 keV) showing the scattered solar X-rays in the equatorial region (blue), and the bright aurorae at the poles (from Branduardi-Raymont et al. 2004). Right: XMM-Newton EPIC spectrum of the disk emission at Jupiter's equator (from Branduardi-Raymont et al. 2007a).

The most interesting X-ray emitting features on Jupiter are those at the poles, where the aurorae show up brightly (Figure 3 left). A much more detailed view of the area is provided by Chandra, which enables us to produce polar projections of the auroral X-ray emissions. Figure 4 shows the overposition of Chandra X-ray photons (green dots) onto the Hubble Space Telescope Imaging Spectrograph (STIS) image (orange) of the northern UV auroral oval: the small dots, concentrated poleward of the oval, are soft X-ray photons (< 2 keV) produced by ionic CX, while the big dots represent hard X-rays (> 2 keV) from electron bremsstrahlung (Branduardi-Raymont et al. 2008).

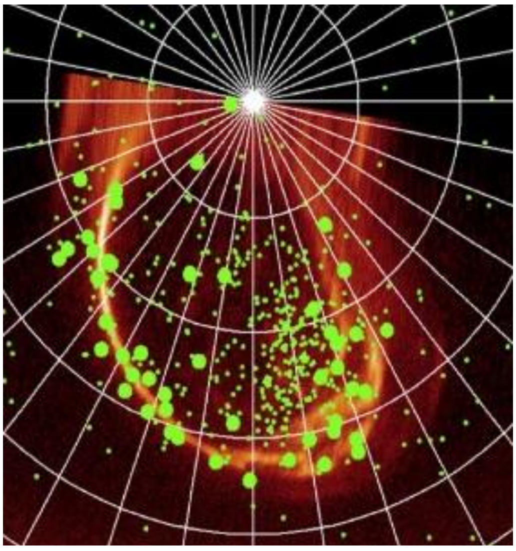


Figure 4. Overposition of Chandra X-ray photons onto the Hubble STIS image (orange) of the northern UV auroral oval: small green dots, soft X-rays from CX; big green dots, hard X-rays from bremsstrahlung (from Branduardi-Raymont et al. 2008).

Energetic considerations indicate that the same population of ~100 keV electrons are likely to be responsible for both emissions. Hence UV and X-ray observations are able to reveal the particle dynamics and electric current systems in Jupiter's complex magnetosphere. The XMM-Newton RGS spectrum (Figure 5) allows to quantify the ion speeds at some 5000 km/s from the width of the ionic CX emission lines (Branduardi-Raymont et al. 2007b).

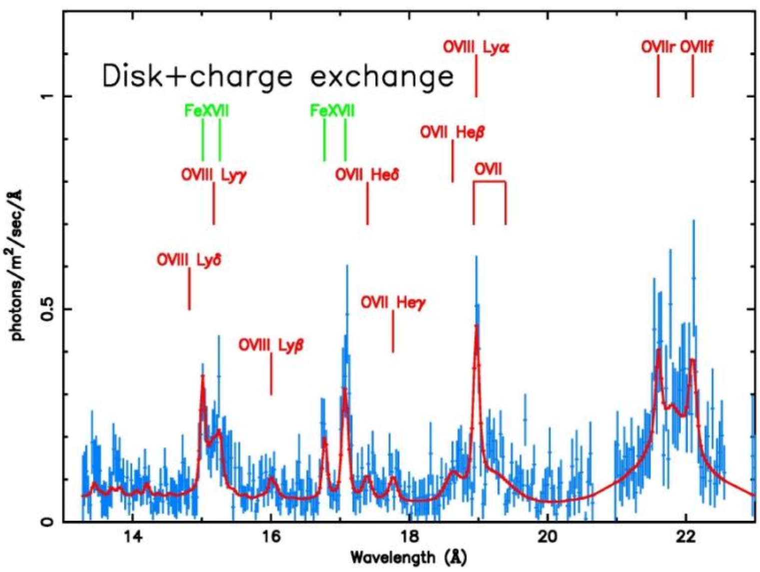


Figure 5. RGS spectrum of Jupiter's combined disk and CX X-ray emissions (from Branduardi-Raymont et al. 2007b).

2.3 Juno at Jupiter

The arrival of Juno (Bolton 2010) at Jupiter in 2016 ushered in a new chapter of our exploration of the giant planet, giving strong impetus to coordinated in situ and remote observations, with exceptional scientific returns. We can take advantage of the synergy between the two measuring approaches in our solar system, but unfortunately not (yet) in exoplanet systems …

As an example of coordinated remote and in situ measurements, Figure 6 (Gladstone and Rymer, private communication) shows an observation at perijove where Chandra photons are overlaid on the Juno UVS (UV imager/Spectrograph, Gladstone et al. 2017) northern auroral oval; the JEDI (Jupiter Energetic particle Detector Instrument, Mauk et al. 2017) precipitating oxygen energy fluxes are also indicated, these being the oxygen ions expected to undergo CX in the planet's atmosphere and produce the observed X-rays.

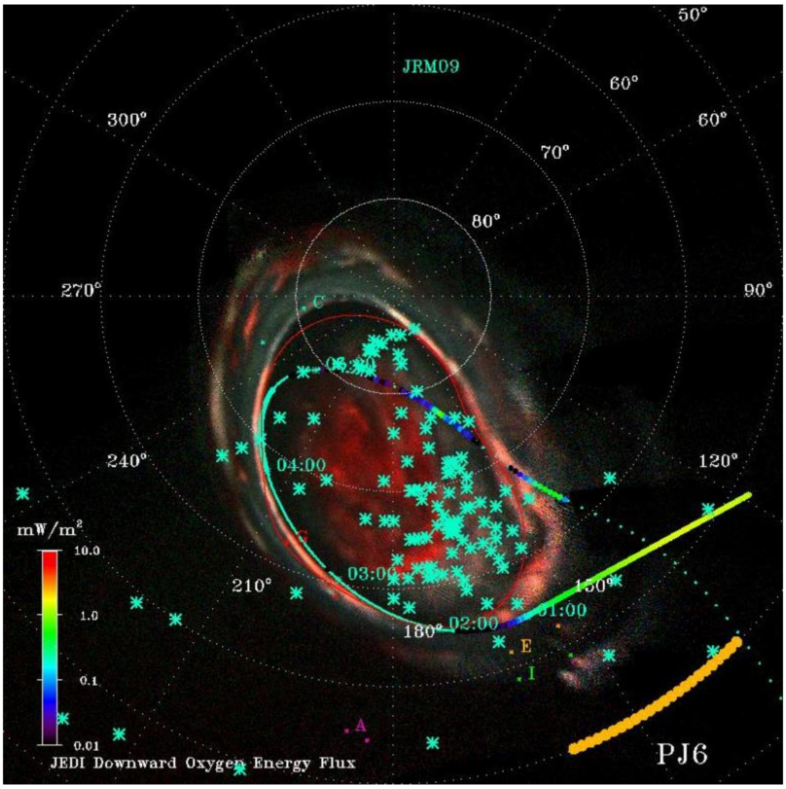


Figure 6. Overlay of Chandra photons (cyan asterisks) on Juno UVS northern auroral oval (pink and grey), with the colour bar indicating the precipitating oxygen energy fluxes. The arc-like sequence of yellow dots in the bottom right hand side shows the average direction of the Sun relative to that polar position during the observation (Gladstone and Rymer, private communication).

The discovery of correlated periodic behaviour of photon and field properties in Jupiter's magnetosphere, exemplified by Figure 7, is another remarkable result of synergetic remote X-ray and in situ measurements with Juno (Dunn et al. 2021a). This has led to a new understanding of the processes taking place in the planet's highly energetic environment in terms of a unification model underpinning particle, waves and magnetic field interactions. In this model Ultra Low Frequency (ULF) compressional waves trigger wave activity in the plasma sheet, driving field-aligned motion of the electrons and ions, which precipitate into the atmosphere to produce Jupiter's bright auroral flares in UV and X-rays, as well as the quasi periodic (QP) radio bursts.

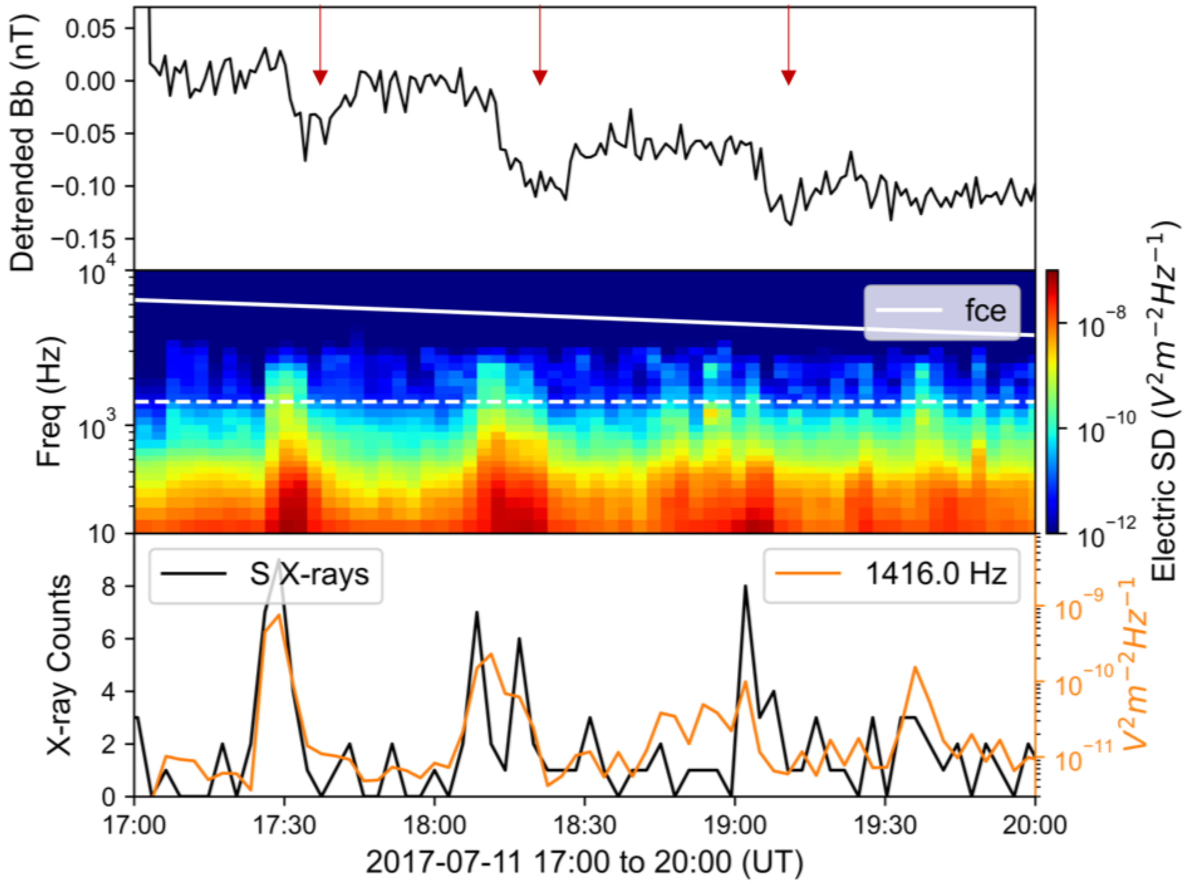


Figure 7. Long timescale connections between Ultra Low Frequency (ULF) magnetic compression-mode waves and quasi periodic radio and X-ray pulses. Top: Ambient magnetic field component from Juno MAGnetometer. Red vertical arrows indicate perturbations from compression-mode ULF waves which trigger wave-particle interactions; these drive field-aligned motion leading the particles to precipitate into Jupiter's poles where correlated bright auroral X-ray flares and quasi periodic radio bursts are produced. Middle: Radio spectrogram from Juno revealing ~45 min kHz whistler-mode hiss pulses. Bottom: XMM-Newton X-ray lightcurve (black) from Jupiter's South pole and timeseries of 1416 Hz emission (orange) (Dunn, private communication).

2.4 Jupiter's moons

Moving on to other bodies in Jupiter's system, Chandra ACIS has detected X-rays from Io and Europa (Elsner et al. 2002), probably coming from energetic H, O and S ions impacting the surface and leading to fluorescence. A peculiar continuum spectrum and a single O emission line have also been detected from the Io Plasma Torus, and have been interpreted as non-thermal electron bremsstrahlung and OVII emissions (Elsner et al. 2002).

Tantalising spectra of Jupiter's moons show a few counts from Chandra ACIS falling at very suggestive energies, e.g. that of neutral oxygen fluorescence (525 eV) in Europa, while Io's spectrum shows count peaks at both oxygen and sulphur (2308 eV) (Nulsen et al. 2020). Fluorescent X-rays can tell us the composition of the moons surface. Recent detection of watery plumes on Europa suggests that X-ray detection could help identify the sub-surface ocean composition.

2.5 More about the solar system

Somewhat unexpectedly, Saturn is a different story from Jupiter. Its disk and polar cap X-ray emissions both have similar coronal-type spectra (unlike Jupiter), and their flux variability appears to be controlled by the Sun, through scattering of solar X-rays as for Jupiter's disk. However, the ACIS spectrum of Saturn's rings is made up of a single 0.53 keV O Ka fluorescent line (Figure 8), suggesting it is due to scattering of solar X-rays on atomic oxygen in the H_2O icy ring material (Bhardwaj et al. 2005b).

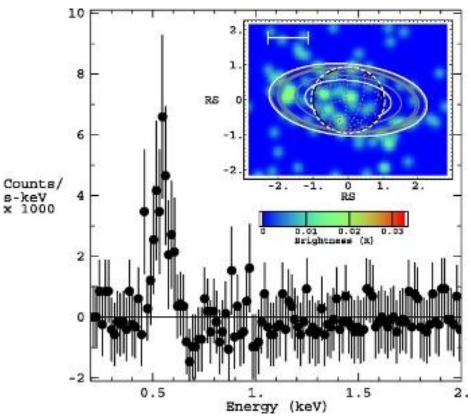


Figure 8. ACIS spectrum of Saturn's ring (from Bhardwaj et al. 2005b)

Continuing with the ice giants, Uranus aurora has been detected in several FUV campaigns (Lamy 2020 and references therein) which revealed extended spots rotating with the planet. Recently the Uranian aurora has also been discovered in X-rays using ACIS data (Dunn et al. 2021b). Figure 9 shows the distribution of X-ray photons in the ACIS image, after re-

registration into Uranus' reference frame, and the concentration of counts on the planet, whose disk is shown by the red circle. The detected X-ray flux exceeds that expected from scattering of solar X-rays at the time: this suggests that a higher albedo than on Jupiter and Saturn, or additional planetary processes, such as an auroral contribution, could be at work on Uranus. Further observations covering several complete rotations of the planet are clearly required to test whether the X-ray fluxes vary in phase with the aurora rotating in and out of view.

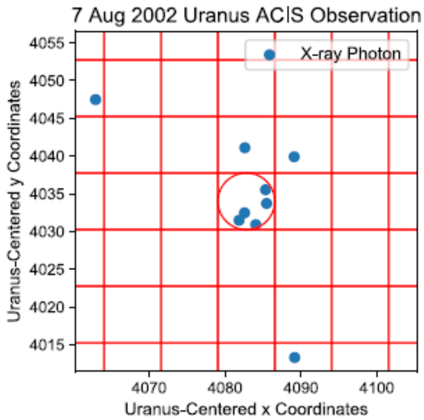


Figure 9. Location of the soft X-ray photons detected by Chandra ACIS and re-registered in Uranus' reference frame. A cluster of photons is coincident with Uranus' disk, represented by the red circle (from Dunn et al. 2021b).

A Chandra ACIS detection of Pluto was also reported (Lisse et al. 2017), but this remains controversial since later XMM-Newton, despite its higher sensitivity, did not confirm the detection.

Turning to the terrestrial planets, Mars' X-ray spectrum is a splendid example of combined emissions from solar wind CX (in the exosphere outflowing from the planet) and solar X-rays scattering (from the planetary disk) which can be separated with the XMM-Newton RGS using a careful selection of emission regions in the cross dispersion direction (Figure 10, Dennerl et al. 2006).

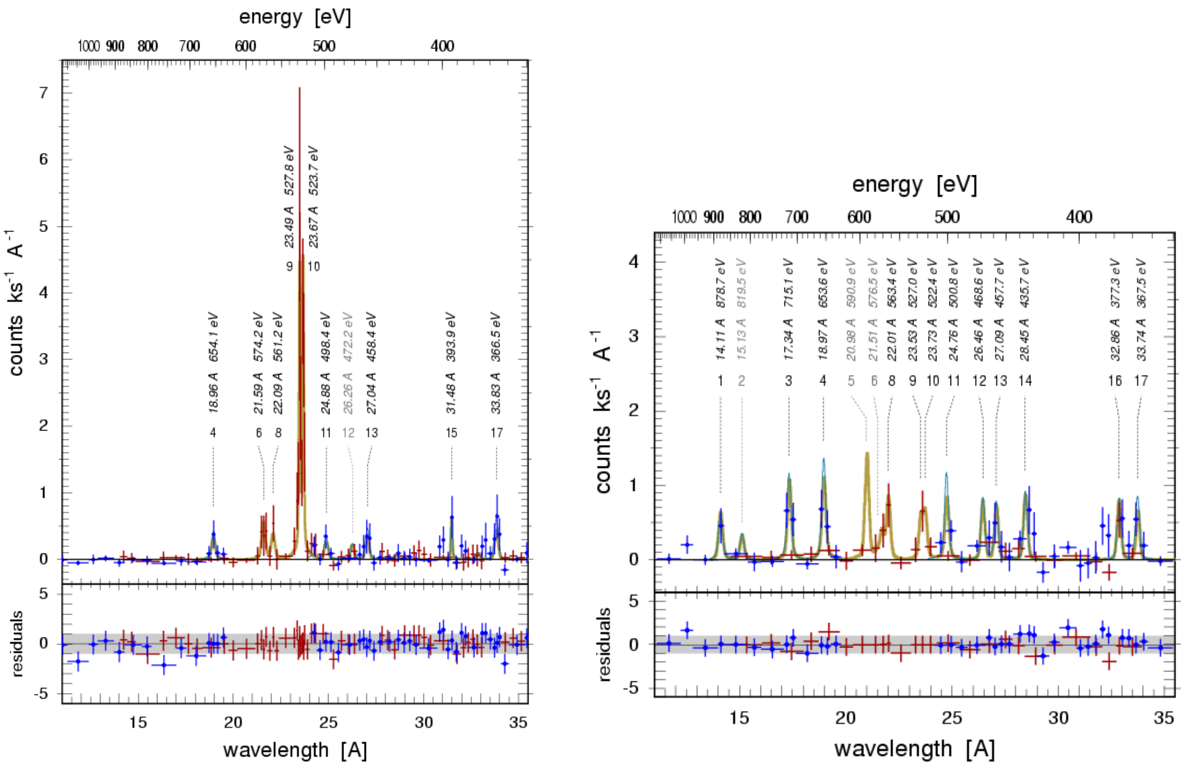


Figure 10. XMM-Newton RGS spectra of Mars: Left, +/– 10” from the planet’s centre, scattered solar X-rays; right, –50” to –15” and +15” to +50”, solar wind CX emission.

A combination of fluorescent scattering and solar wind CX is observed also at Venus: however, CX can only be detected at solar minimum, because scattering of solar X-rays in the very dense atmosphere of the planet outshines CX at solar maximum (Dennerl 2008).

Comets are exceptional sources of X-rays by solar wind CX when they are close to the Sun (Dennerl et al. 2003). Comparison of the visible and X-ray appearance of a moderately optically bright comet shows the latter to be filling the whole XMM-Newton EPIC field of view (30’ size): with spectra essentially composed of multiple emission lines from a variety of ion species, comets are probes of solar wind properties as they travel through it at changing distances from our star.

2.6 Back to Earth

Finally to our Earth itself: X-rays produced in the aurorae (above 2 keV) were most clearly detected and studied with the PIXIE instrument on the Polar spacecraft, which established the hard X-rays to be due to bremsstrahlung from precipitating electrons (Østgaard et al. 2001). Chandra HRC observed the Earth's soft X-ray aurora morphology showing it to be highly variable, with elongated structures, intense multiple arcs, diffuse patches, at times absent (Bhardwaj et al. 2007), but did not return a spectrum, so we do not know if it may contain any CX contribution.

The Moon was one of the first solar system bodies to be observed in X-rays: ROSAT provided the first soft X-ray image in 1990. The sunlit portion of the Moon was clearly visible, as well as a distinct X-ray shadow in the diffuse X-ray background cast by the dark side of the Moon. However, some residual X-ray emission was noticed on the night side: this was a clue for what was realised only some ten years later, that X-rays are also produced in the Earth's surroundings when the solar wind encounters the magnetosphere (Wargelin et al. 2004).

Let's consider the impact of a coronal mass ejection (CME) from the Sun arriving at the Earth. It will compress the magnetosphere, and for favourable conditions of magnetic field orientations (e.g. interplanetary magnetic field pointing south, so that magnetic reconnection is more likely to occur on the dayside) solar wind plasma can penetrate into the magnetosheath. We now know that X-rays are produced in the dayside magnetosheath and the cusps by the process of solar wind CX.

The ultimate consequences of this type of encounter are geomagnetic storms and particle precipitation into the polar regions, where the aurorae are the footprints of this whole interaction. A novel mission called SMILE (Solar wind Magnetosphere Ionosphere Link Explorer, Branduardi-Raymont et al. 2018) is under development: it will image and monitor the solar wind CX soft X-ray emission in the magnetosheath to study solar-terrestrial interactions in a global way never attempted before. SMILE combines X-ray imaging of the dayside magnetosheath and the cusps, simultaneous UV imaging of the northern aurora and in situ monitoring of the solar wind and magnetosheath plasma conditions from a highly elliptical polar orbit. Its scientific objectives are to understand the details of solar-terrestrial relationships, the roles of magnetic reconnection in the physical processes involved, what triggers and drives the geomagnetic storm cycle and the consequences of CME-induced storms.

3 DISCUSSION AND CONCLUSIONS

Looking ahead, Chandra and XMM-Newton combined have demonstrated the potential of planetary X-ray astronomy, in particular by establishing CX as the process that provides global and remote X-ray diagnostics of plasma interactions, in the solar system and throughout the Universe. CX allows us to observe planetary responses, including Earth's, to solar stimuli, and missions like SMILE will provide direct scientific inputs to space weather studies.

The future of planetary remote X-ray observations is bright because we are building more and more knowledge with Chandra and XMM-Newton capabilities while we are preparing for the giant advances that Athena will bring about in a decade. However, the ultimate goal is to have X-ray observations in situ at the planets, to provide the necessary sensitivity and spatial/energy resolution that can really establish X-rays on a par with other wavebands in planetary exploration. We have indeed started on this path, with BepiColombo carrying X-ray imagers to Mercury to explore surface fluorescence, and SMILE, as well as other missions proposed and under development, targeting the study of solar-terrestrial interactions.

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CONFLICT OF INTEREST

The authors declare no financial or commercial conflict of interest.

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