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Solar system X-rays from charge exchange processes

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While X-ray astronomy began in 1962 and has made fast progress since then in expanding our knowledge about where in the Universe X-rays are generated by which processes, it took one generation before the importance of a fundamentally different process was recognized. This happened in our immediate neighborhood, when in 1996 comets were discovered as a new class of X-ray sources, directing our attention to charge exchange reactions. Charge exchange is fundamentally different from other processes which lead to the generation of X-rays, because the X-rays are not produced by hot electrons, but by ions picking up electrons from cold gas. Thus it opens up a new window, making it possible to detect cool gas in X-rays (like in comets), while all the other processes require extremely high temperatures or otherwise extreme conditions. After having been overlooked for a long time, the astrophysical importance of charge exchange for the generation of X-rays is now receiving increased general attention. In our solar system, charge exchange induced X-rays have now been established to originate in comets, in all the planets from Venus to Jupiter, and even in the heliosphere itself. In addition to that, evidence for this X-ray emission mechanism has been found at various locations across the Universe. Here we summarize the current knowledge about solar system X-rays resulting from charge exchange processes.

1 Introduction

The history of X-ray astronomy is closely related to solar system studies: the first attempts ever to detect X-rays from a celestial object concentrated onto the Sun (Friedman et al. 1951), and the (unsuccessful) attempt to detect X-rays from the Moon, in 1962, is generally considered as the birth of X-ray astronomy (Giacconi et al. 1962). In this context, it is interesting to note that it was again a solar system object which considerably enhanced our view of the X-ray Universe, when comet C/1996 B2 (Hyakutake) was discovered to be an X-ray source (Lisse et al. 1996). This came after Hudson et al. (1981) failed to detect soft X-rays from comet Bradfield (1979l) using the Einstein X-ray satellite, discouraging X-ray observers from further studies of comets.

However, the unexpected Hyakutake finding, which was soon followed by the discovery of X-rays from other comets (Dennerl et al. 1997), has revealed the presence of a process which appears to have been overlooked in its importance for the generation of X-rays before: charge exchange between highly charged ions and neutrals. This process, taking place between solar wind heavy ions and cometary neutrals, was found to be the explanation for the cometary X-rays (Cravens 1997).

Comets, however, are not the only location where X-rays are produced by charge exchange. In our solar system, this process has been found to occur in all the planets from Venus to Jupiter, and even in the heliosphere itself. As interactions between highly charged ions and neutrals are not limited to our solar system, charge exchange is likely to produce X-rays at many other places in the Universe, and in recent years observational evidence for the presence of this process at some of these locations may have been found.

While the importance of the charge exchange process for X-ray astrophysics was not generally recognized before the discovery of cometary X-ray emission in 1996, the process itself has been known for a very long time. As charge exchange reactions are likely to occur whenever ions encounter neutrals, one may argue that they have accompanied atomic physics from its very beginning, starting with scattering experiments of He ions in solids by Geiger & Marsden (1909). A recent review about the various aspects of charge exchange studies in a historical context, with specific emphasis on X-ray astrophysics, is given by Dennerl (2010). Here we summarize the current knowledge about solar sys-

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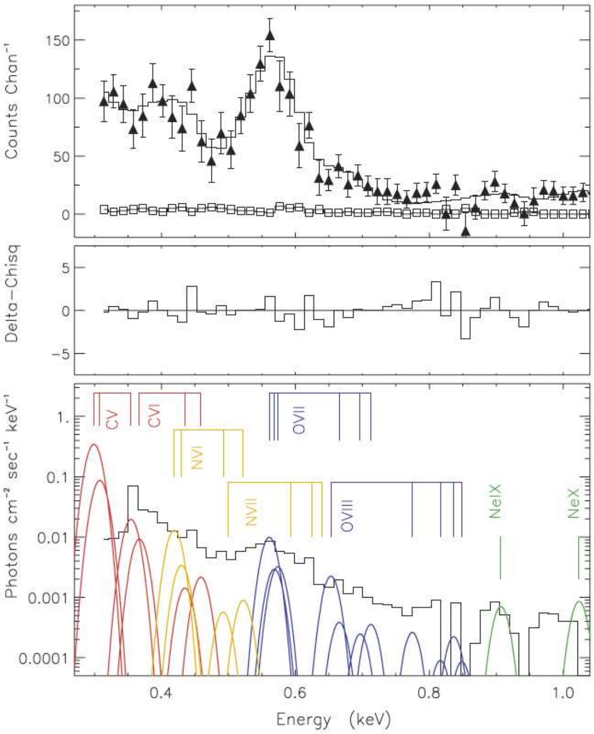

Fig. 1 (online colour at: www.an-journal.org) X-ray spectrum of the B fragment of comet 73P/SW3. *Top panel*: observed Chandra ACIS-S count rate spectrum (triangles) with that resulting from the best fit charge exchange model (histogram) and a sample background (open squares). *Middle panel*: residuals of the best fit model. *Bottom panel*: charge exchange model with the observed spectrum, normalized to yield the incident flux in photons cm^{-2} s^{-1} keV^{-1}, through smeared by the spectral resolution of the detector (from Wolk et al. 2009).

tem X-rays resulting from charge exchange processes. Note, however, that charge exchange is not the only source of X-ray emission found in the solar system – scattering of solar X-rays and auroral precipitation processes also produce important amounts of sensible X-rays. A good overview of all the various X-ray processes taking place in the solar system is given by Bhardwaj et al. (2007a).

In Sect. 2 we focus on comets, which provide the best case for studying the physics of charge exchange. Section 3 summarizes our current observational knowledge about this process in planets. We skip the topic of charge exchange in the heliosphere, because this will be covered in the contribution by Koutroumpa (2012). In Sect. 4 we discuss current challenges in the observational study of solar system charge exchange and show how this field can be substantially advanced by future space missions. The main conclusions will then be summarized in Sect. 5.

2 Charge exchange in comets

Comets play a central role in the investigation of the charge exchange process, because their X-ray emission is the direct result of this interaction between highly charged heavy ions in the solar wind and cometary neutrals. As the gas around comets is cold, there is essentially no thermal X-ray emission, and as it is not subject to a strong electric or magnetic field, X-ray emission by energetic electrons is negligible. Furthermore, the cometary nucleus is so small, and the gas and the embedded dust grains are so diluted, that there are not enough targets for solar X-ray scattering to become important. This has the exciting consequence that the X-ray emission of comets is essentially pure charge exchange emission (Fig. 1).

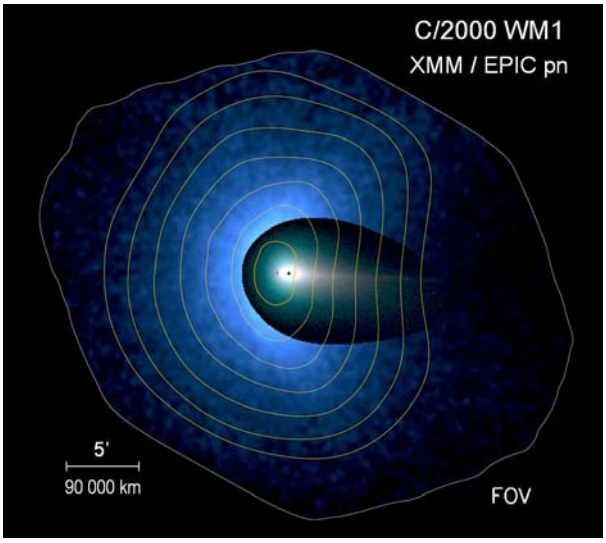

Fig. 2 (online colour at: www.an-journal.org) XMM-Newton / EPIC-pn image of comet C/2000 WM1, exhibiting the large extent of the X-ray emission (outer blue image with contour lines) compared to the extent in the optical (inset, at the same scale; from Dennerl et al. 2003).

Thus, comets represent perhaps the best laboratory for studying the physics of charge exchange. With highly charged heavy ions streaming into the cold, tenuous cometary gas, nature is providing a clean experimental setup and a textbook example of a system which is far away from thermal equilibrium. For observing such a system, the full range of capabilities of current X-ray instrumentation, mainly their spatial, temporal, and spectral resolution, can be utilized: the cometary X-ray emission is so extended that it can be spatially resolved, allowing studies of its morphology, the temporal resolution makes it possible to correct for the apparent motion and to investigate the temporal variability of the X-ray signal, and spectral resolution is the key for revealing the elusive properties of charge exchange.

After it was realized that cometary X-ray emission is the result of charge exchange between heavy solar wind ions and neutral gas, it became obvious that comets can be used as natural probes for monitoring the heavy ion content of the solar wind (Dennerl et al. 1997; Kharchenko & Dalgarno 2000), because each ion leaves its characteristic signature in the X-ray spectrum. Around solar minimum, two types of solar wind are present: a fast ($v \sim 700\ \mathrm{km\,s}^{-1}$), steady polar component at latitudes above ~ 20 degrees, characterized by low density and low ionization, and an equatorial component, which is typically slow ($v \sim 400\ \mathrm{km\,s^{-1}}$), dense, and highly ionized, but also highly variable in these parameters. Outside solar minimum, the equatorial component is expanding to higher latitudes, so that the clear distinction between both components disappears around solar maximum. Before the discovery of cometary X-ray emission, an investigation of the chemical composition and ionization state of the solar wind required in-situ measurements, and to date only one instrument, SWOOPS on Ulysses (Bame et al. 1992), was able to perform such measurements at high heliographic latitudes (McComas et al. 2003).

In this context, the cometary X-ray emission holds a high scientific potential. The large extent of the cometary coma combined with the large cross section for charge transfer reactions (10^{-15} cm^2 compared to, e.g., 10^{-18} cm^2 and less for scattering) makes comets act as sensitive sensors (cf. Fig. 2) which probe ly the heavy ion content of the solar wind and transmit this information by electromagnetic radiation (X-rays) over large distances. Moreover, due to the fact that, unlike all other solar system objects, the paths of comets are not confined to low ecliptic latitudes, a full 3D sampling of the solar wind is possible. As the Oort cloud and the Kuiper belt provide, on the long-term average, a constant supply of comets, the solar wind can be monitored over all phases of the 11-year solar activity cycle. Thus, comets are ideally suited for deriving observational information about fundamental properties of the solar wind, which would be very difficult to obtain otherwise. This information is not only important for our understanding of the Sun, but also of solar-type stars in general.

Bodewits et al. (2007) analyzed the X-ray spectra of all the comets, eight in total, which were studied with the Chandra X-ray observatory in the period 2000 to 2006, covering the transition from solar maximum to solar minimum. Figure 3a shows the (background subtracted raw) spectra of all the comets, and Figs. 3b, c show at which ecliptic latitude and phase in the solar cycle the spectra were observed. It is immediately obvious that there are spectral differences. In Fig. 3a, three spectral bands are indicated, dominated by emission from (i) C V, C VI, N VI ('C+N'), (ii) by O VII, and (iii) by O VIII ions, and the spectra are arranged so that, from top to bottom, flux is systematically shifted from lower to higher energy bands. The quantitative results of the spectral fits clearly show that the flux in the C+N band is anticorrelated to that in the O VIII band (Fig. 3d), indicating that the comets were exposed to different solar wind conditions.

As can be seen in Figs. 3b and 3c, all the comets which were observed at high latitudes happened to be there during solar maximum, when the equatorial solar wind had expanded into these regions. This implies that, until 2006, Chandra had not observed any comet exposed to the polar wind. This situation changed in October 2007, during solar minimum, when the nucleus of comet 17P/Holmes experienced a spectacular outburst, which increased its dust and gas outflow and optical brightness by almost a million times within hours, from under 17 mag to 3 mag, making it by far the optically brightest comet observable by Chandra since its launch. At the time, comet 17P/Holmes was located at a sufficiently high heliographic latitude (19°) to be exposed to the polar wind at solar minimum. It was thus expected that this comet would exhibit considerably different X-ray properties, and in fact this was observed: 17P/Holmes became the first comet where Chandra did not detect any significant X-ray emission at all (Christian et al. 2010). The most likely explanation for this dramatic X-ray faintness is that the polar wind was so diluted and its ionization so low that only very little X-ray flux was generated by charge exchange at energies above ~ 300 eV. An instrumental effect, i.e., a loss of sensitivity, can definitively be ruled out, because only two months later, another comet, 8P/Tuttle, was observed with Chandra, and this comet, at low latitude (3°), was clearly detected in X-rays (Christian et al. 2010).

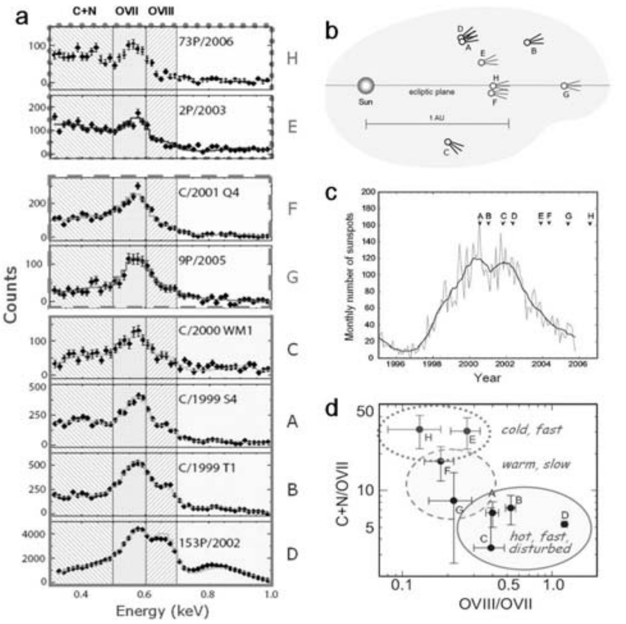

Fig. 3 Summary of the spectral results obtained with Chandra for all the comets (denoted by A–H) which were observed from 2000 to 2006: *a*) the 0.3–1.0 keV pulse height distributions, *b*) the ecliptic latitudes and *c*) phases in the solar cycle of the observed comets, and *d*) the deduced information about the solar wind heavy ion content. Fig. 3 a,c,d were adapted from Bodewits et al. (2007).

While comets allow us to sample the solar wind heavy ion content at locations which are inaccessible by in-situ measurements, there is also, occasionally, the opportunity to compare the X-ray observations with independent in-situ measurements of the solar wind heavy ion content. This happens when comets come sufficiently close to the Earth that the solar wind composition measured with satellites like SOHO, WIND, or ACE near Earth can be reliably extrapolated to the position of the comet. Such favorable close encounters happened in 1996 with comet C/1996 B2 (Hyakutake; Lisse et al. 1996; Neugebauer et al. 2000), in 1997 and 2003 with 2P/Encke (Lisse et al. 1999; Lisse et al. 2005), in 2006 with 73P/SW-3 2006 (Wolk et al. 2009), and in 2011 with 45P/HMP (Dennerl et al., in prep.).

While the possibility to combine remote observations with in-situ measurements is already a rare fortunate situation in astrophysics, there is yet another, even more exciting possibility: to perform active experiments with comets. This happened on 2005 July 4, when the 372 kg projectile of the Deep Impact mission was targeted to collide with the nucleus of comet 9P/Tempel 1. This unique event was monitored in X-rays with the satellites Chandra (Lisse et al. 2007), XMM-Newton (Schulz et al. 2006), and Swift (Willingale et al. 2006), not only during the time of the impact, but also on several occasions from 4 days before to 2 months afterwards. The X-ray signal of comet 9P/Tempel 1 was found to be quite variable, exhibiting two impulsive events on June 30 and July 8. While both were coincident with increases in the solar wind flux arriving at the comet, the June 30 flare coincided also with an increase of the comet's outflow rate, unrelated to the later impact (Lisse et al. 2007). These peaks were much stronger than any increase in the X-ray flux which might have been caused by the impact itself. It could not be unambiguously proven that changes in the X-ray flux at and after the impact were indeed associated with the impact.

The examples above have illustrated what can be learned from X-ray spectroscopy and photometry. But also the spatial distribution of the diffuse X-ray emission of a comet contains valuable information, because it provides a two-dimensional global view of the interaction between the solar wind and the cometary gas (Fig. 2). This information can be used to disentangle the effects of the gas production rate and the solar wind heavy ion flux, which both determine the total X-ray luminosity of a comet, because the spatial morphology depends mainly on the gas production rate, while the emission intensity is proportional to the heavy ion flux (Wegmann et al. 2004). A well calibrated X-ray image of a comet, cleaned from any other unrelated X-ray sources, can even be utilized to obtain information on the position, shape and structure of the bow shock (Wegmann & Dennerl 2005). The bow shock can otherwise only be studied with spacecraft encounters, which give plasma parameters just along a one-dimensional line, typically passing though the flanks of the shock, but not through the subsolar part.

In short, comets can be considered as the best natural laboratory for studying charge exchange processes. They have demonstrated the efficiency of these processes for creating X-rays and have directed our attention to the fact that nature is capable of producing extremely favorable conditions for the generation of charge exchange induced X-ray emission. Thus, X-ray observations of comets can be considered as benchmarking experiments for testing our understanding of the physics of charge exchange. They may provide fundamental data for atomic physics, which, when fed into plasma emission codes, are likely to improve plasma diagnostics in general. Moreover, they provide valuable information about properties of the solar wind, and its interaction with the cometary gas, which are very difficult to obtain otherwise.

3 Charge exchange in planets

In principle, the gas in planetary atmospheres should respond to the incident flux of solar wind ions in a similar way as cometary gas. Observationally, however, remote studies of charge exchange in planetary atmospheres are more challenging, because of the bodies' small apparent size combined with the presence of additional emission components: (i) their considerably higher atmospheric density provides a sufficient number of target atoms for scattering of solar X-rays to become efficient, (ii) if a magnetic field is present, it may deflect and accelerate charged particles, causing X-rays also to be emitted by bremsstrahlung of energetic electrons. A magnetic field may further deflect the incident ions or change their ionization state, thus affecting the charge exchange process.

In the following, we briefly summarize what is currently known about charge exchange induced X-ray emission in planets, starting with Mars, which is the best planetary analog to a comet, followed by Venus, where charge exchange is more challenging to observe. We then proceed to the magnetic planets Jupiter and Earth, and conclude this section with the remaining planets Saturn, Uranus, Neptune, and Mercury, where no evidence for charge exchange has been found to date.

3.1 Mars

First indications for the presence of charge exchange induced X-ray emission at Mars were found in the first Chandra observation of this planet, in July 2001. While the X-ray signal was dominated by fluorescent scattering of solar X-rays, there was also some evidence for a faint X-ray halo exhibiting a different spectrum. This evidence, however, was based on only 34.6 ± 8.4 excess counts relative to the background (Dennerl 2002).

A subsequent XMM-Newton observation, performed in November 2003 during a period of high solar activity, confirmed the presence of this halo and allowed detailed studies to be made (Dennerl et al. 2006): about 12 emission lines were found in the spectrum of the halo which could be attributed to the de-excitation of highly ionized C, N, O, and Ne atoms, as expected for charge exchange. The He-like O VII triplet was found to be dominated by the spin-forbidden magnetic dipole transition $2^3\mathrm{S}_1 \rightarrow 1^1\mathrm{S}_0$ (Fig. 4, top), confirming that the X-ray halo around Mars is indeed caused by charge exchange. By utilizing the imaging capabilities of the Reflection Grating Spectrometer (RGS) onboard XMM-Newton (Fig. 4, bottom), it was also possible

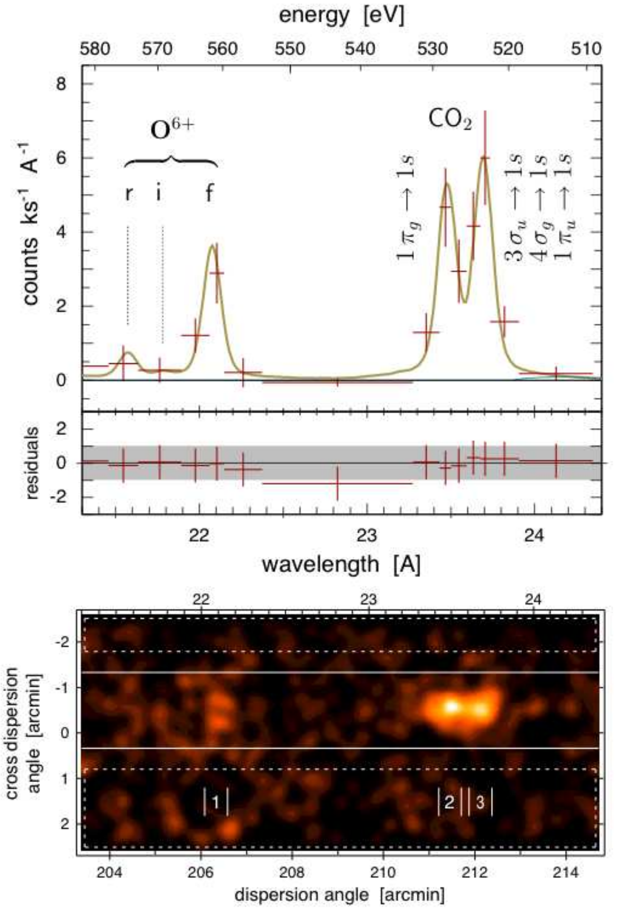

Fig. 4 (online colour at: www.an-journal.org) Imaging spectroscopy of Mars with XMM-Newton / RGS in November 2003. *Top*: RGS spectrum obtained from a $100''$ wide area along the cross dispersion direction, showing the region around the CO$_2$ doublet and the O VII multiplet. *Bottom*: dispersed images in the same wavelength/energy range as above. The apparent diameter of Mars during this observation was $12.2''$ (from Dennerl et al. 2006).

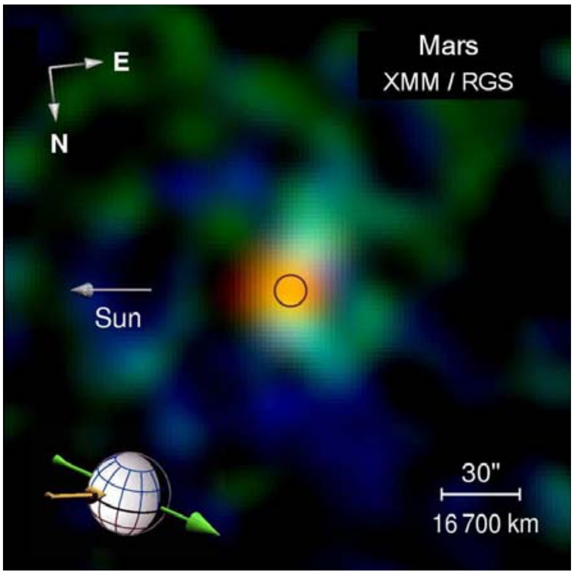

Fig. 5 (online colour at: www.an-journal.org) X-ray image of Mars, obtained in November 2003 with XMM-Newton / RGS in the emission lines of charge exchange (green-blue) and fluorescence of solar X-rays (orange). The black circle indicates the size of the planet (from Dennerl et al. 2006).

to obtain monochromatic maps, which contain valuable information about where the individual emission lines originate. A color image composed of these maps (Fig. 5) reveals a bowshock-like structure, which results from the combination of exospheric gas density and solar wind heavy ion flux.

Due to the high cross sections of $\sim 10^{-15}$ cm^2, charge exchange induced X-rays are a most sensitive tracer of tenuous amounts of gas (cf. Fig. 2). With XMM-Newton, the X-ray emission could be traced out to ~ 8 Mars radii, extending into exospheric regions far beyond those that have been observationally explored before. This is particularly interesting, because charge exchange between atmospheric constituents and solar wind ions is considered an important nonthermal escape mechanism, which may be responsible for a significant loss of the Martian atmosphere. Although this escape process is mainly caused by charge exchange with solar wind protons, which are ~ 1000 times more abundant than heavy ions and which do not produce X-rays, the observable X-rays are a valuable tracer of this process. Thus, X-ray observations, providing a novel method for studying exospheric processes on a global scale, may lead to a better understanding of the present state of the Martian atmosphere and its evolution. They open up a completely new possibility of remote, global imaging of planetary exospheres, and their spatial and temporal variability.

A first review about the early X-ray observations of Mars, performed around solar maximum, is presented by Dennerl (2006). Later observations, around solar minimum, indicated that the X-ray luminosity of Mars is highly correlated with the solar activity cycle. In April 2008, Mars was so X-ray faint that it was not even detectable with Suzaku (Ishikawa et al. 2011).

3.2 Venus

Compared to Mars, the observational study of charge exchange induced X-rays is considerably more challenging at Venus. One reason is that the angular separation of Venus from the Sun, as seen from Earth, never exceeds 47.8°, and that most imaging X-ray astronomy satellites cannot observe objects which are closer than 70° from the Sun. A remarkable exception is Chandra, which can be pointed to objects as close as 45.6° from the Sun. This is just sufficient to observe Venus during the brief episodes of favorable greatest elongation.

Another observational challenge is the optical brightness of Venus. With an optical surface brightness of at least 1.2 mag per square arcsecond, Venus is the third brightest source in the optical sky, right after the Sun and the Moon. As X-ray CCDs are intrinsically also sensitive to optical

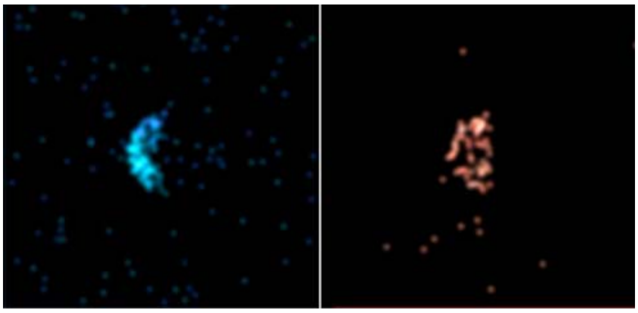

Fig. 6 (online colour at: www.an-journal.org) Distribution of X-ray photons from Venus, obtained with Chandra ACIS-I on 2006 March 27, in the energy ranges which are dominated by charge exchange (*left*) and by fluorescence (*right*) (adapted from Dennerl 2008).

light, they are equipped with optical blocking filters. These filters, however, must not be too thick, because they would otherwise also block too much of the X-rays. It turned out that the optical blocking filter used in the Chandra ACIS-I CCDs is just sufficient for X-ray observations of Venus.

Yet another observational challenge for the study of charge exchange induced X-rays is the fact that the mass of Venus exceeds that of Mars by a factor 7.6. This has the consequence that the exosphere of Venus is considerably more condensed (Gunell et al. 2007), so that even with the unprecedented spatial resolution of Chandra, a clear spatial separation between fluorescent scattering of solar X-rays in the upper atmosphere and charge exchange induced X-rays in its exosphere is not possible.

In the first Chandra observation of Venus, in January 2001, at solar maximum, the X-ray flux was dominated by fluorescence of solar X-rays, and no other source of emission was detectable (Dennerl et al. 2002). It became obvious that, in order to unambiguously detect charge exchange induced X-rays, the fluorescent flux would need to be suppressed. Fortunately this happens naturally with time, because the solar X-ray flux gets considerably reduced towards solar minimum, while the equatorial solar wind flux is less affected by the solar cycle.

Thus, it was expected that the relative contribution of charge exchange should increase towards the solar minimum, and this was indeed observed: in the second Chandra observation of Venus, in March 2006, solar fluorescence was sufficiently attenuated to allow the detection the presence of another emission component (Dennerl 2008): images composed of photons with energies where charge exchange induced emission (Fig. 6, left) and fluorescence of solar X-rays (Fig. 6, right) was expected, exhibited a different morphology. In the first case, the limb brightening was considerably higher, in agreement with the results of simulations (Gunell et al. 2007).

In a third Chandra observation, in October 2007 at solar minimum, the fluorescence component was practically absent, but the charge exchange flux was also very low. Nevertheless, the brightest emission line in the spectrum was found at 0.56 keV, consistent with O VII emission of solar wind O^{7+} ions, undergoing charge exchange with neutrals in the Venusian exosphere (Dennerl 2008). The O VII emission line is typically the brightest feature in the charge exchange spectra of comets (cf. Figs. 1 and 3).

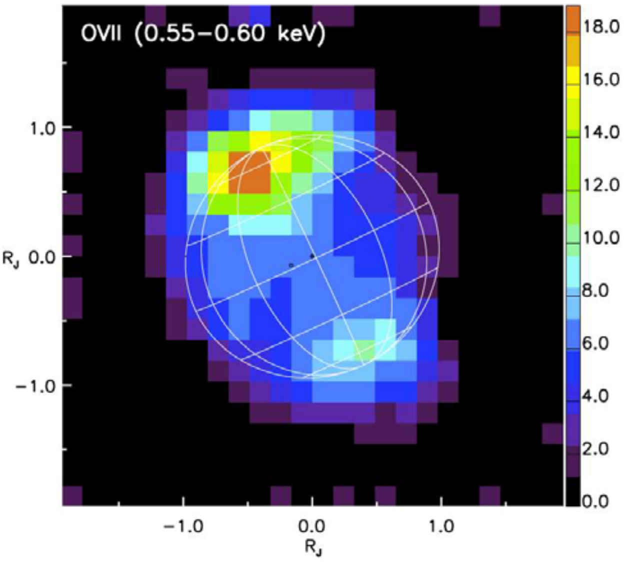

Fig. 7 (online colour at: www.an-journal.org) XMM / EPIC image of Jupiter in the narrow spectral band 0.55–0.60 keV, which covers charge exchange from O^{7+} ions (cf. Fig. 8). This image was obtained in November 2003 (from Branduardi-Raymont et al. 2007).

3.3 Jupiter

Charge exchange occurs also at Jupiter, the planet with the highest magnetic field in the solar system. The strong magnetic field, however, modifies the charge exchange process considerably, because it deflects and accelerates the heavy ions, so that the charge of the ions which precipitate at high kinetic energies into the atmosphere may increase and decrease many times in sequential collisions with the atmospheric gas. Thus, the X-ray spectra depend strongly on the kinetic ion energies, while in the nonmagnetic case they are determined by the composition of the solar wind (Kharchenko et al. 2008).

The strong magnetic field does not only modify the charge exchange process, but has also influenced its investigation, because it makes Jupiter a powerful X-ray source. X-rays from Jupiter were already detected in 1979 and 1981 with the Einstein satellite (Metzger et al. 1983). In order to explain the X-ray flux as well as the high UV flux which was observed in the auroral regions with the Voyager 1 and 2 spacecraft and the International Ultraviolet Explorer (IUE) satellite, charge exchange was already considered in 1988 by Horanyi et al. as one of the basic processes in their theoretical modeling of the energy deposition by precipitating energetic oxygen ions. The other processes were electron stripping, dissociative and nondissociative ionization, exci-

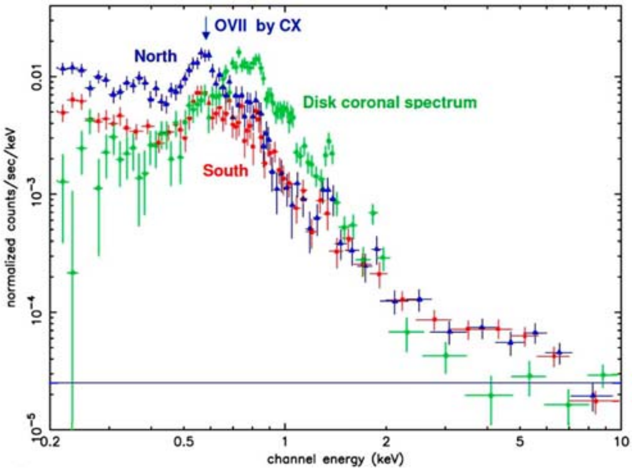

Fig. 8 (online colour at: www.an-journal.org) X-ray spectra of Jupiter for the north (blue) and south (red) aurora, and of the low latitude disk emission (green). The auroral spectra exhibit evidence for charge exchange; the most prominent emission line resulting from O^{7+} ions is marked (adapted from Branduardi-Raymont et al. 2007).

tation, and elastic collisions. Cravens et al. (1995) extended this model, which had originally included only the lowest four charge states of oxygen, to all its charge states, and concluded that the auroral X-ray emission of Jupiter observed with the Rosat satellite can be explained by heavy ion precipitation. A detailed interpretation, however, was hampered by the limited spatial and spectral resolution available. A review of the early investigation of Jupiter's X-ray emission is given by Bhardwaj & Gladstone (2000).

Substantial progress was obtained with the satellites Chandra and XMM-Newton. They showed that there is an equatorial component which is predominantly caused by scattered solar X-rays (Bhardwaj et al. 2005a), similar to Venus and Mars, and indicated that charge exchange is the basic explanation of the polar component for X-ray energies below ∼2 keV (Branduardi-Raymont et al. 2004, 2007), while bremsstrahlung of energetic electrons precipitating from the magnetosphere may be responsible for the X-ray emission at higher energies (Branduardi-Raymont et al. 2007). In contrast to the nonmagnetic planets, however, where the heavy ions are supplied by the solar wind, the heavy ions could also originate from the Jovian magnetosphere, by acceleration and subsequent additional ionization of ambient sulfur and oxygen ions in a field-aligned potential, as explored by Cravens et al. (2003), who considered the second possibility more likely. Also Hui et al. (2010) favored the idea that ions of magnetospheric origin dominate in driving the auroral X-ray emission, because their fits to the Chandra and XMM-Newton X-ray spectra of the Jovian aurora showed in general no improvement by including carbon, which would be abundant in the solar wind.

Independent of the origin of the heavy ions, it appears now to be generally accepted that charge exchange is likely to be responsible for the soft X-ray emission observed in the polar regions of Jupiter, with O VII providing the dominant contribution (Figs. 7 and 8), like in comets (cf. Figs. 1 and 3).

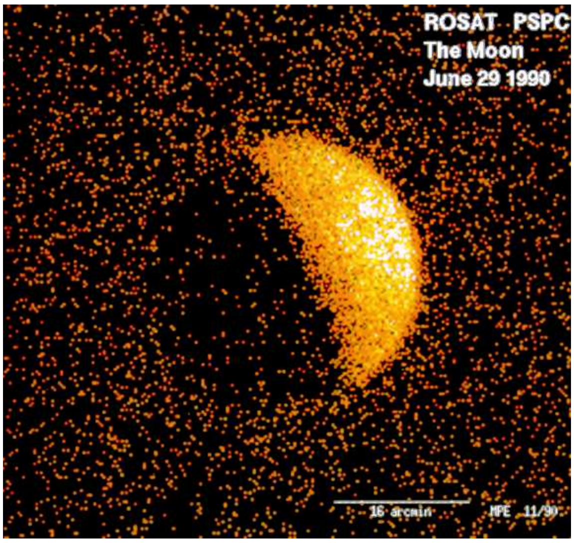

Fig. 9 (online colour at: www.an-journal.org) Rosat X-ray image of the Moon (from Schmitt et al. 1991). The faint diffuse flux contribution which is evident on the dark side of the Moon is mainly caused by charge exchange processes in the Earth's exosphere.

3.4 Earth

Although the Earth resembles Jupiter in the presence of an atmosphere and a magnetic field, which together generate auroral X-ray emission, superimposed on scattered solar X-rays from the sunlit hemisphere, there are also marked differences between these planets. In contrast to Jupiter's aurora, which is largely powered by energy extracted from planetary rotation, Earth's aurora is generated through the interaction of the solar wind with the magnetosphere (Waite et al. 2001), and its X-ray emission is not caused by charge exchange of energetic heavy ions, but by bremsstrahlung from precipitating electrons accompanied by characteristic K-shell line emissions from nitrogen and oxygen (Bhardwaj et al. 2007b). Charge exchange, however, does occur in the Earth exosphere, or geocorona. While this has been known for a long time, its implications for X-ray astronomy were not realized before the discovery of cometary X-rays: the Earth is surrounded by an extended X-ray emitting cloud (similar to Mars, cf. Fig. 5), which superimposes a diffuse X-ray glow to observations from a low Earth orbit. This specific viewing geometry makes it very challenging to disentangle the X-ray emission resulting from charge exchange interactions in the geocorona from the diffuse X-ray emission beyond.

The most straightforward technique is to look at the dark side of the Moon, because there any X-ray emission from behind is blocked. Figure 9, taken with Rosat from a low Earth orbit, shows the presence of a faint diffuse X-ray glow (Schmitt et al. 1991), which is now understood as foreground emission created by charge exchange processes in the geocorona. Another method to discriminate geocoronal (and heliospheric) from extrasolar X-ray emission is to utilize its temporal variability, as demonstrated by Snowden et al. (2004). Carter & Sembay (2008) performed extensive systematic investigations of the XMM-Newton data archive in order to identify observations which were affected by charge exchange. The most extreme case exhibited a rich emission line spectrum up to Si XIV at 2.0 keV, indicating that a cloud of plasma associated with a coronal mass ejection had passed the geocorona (Carter et al. 2010).

While temporal variability studies are capable of identifying periods of enhanced geocoronal (and heliospheric) X-ray flux, they cannot be used to determine the zero level of the quiescent component. In recent years, the potential implications of the presence of such a foreground component for studies of extended soft X-ray sources have received increased attention, in particular in investigations concerning the nature of the Local Hot Bubble.

3.5 Saturn, Uranus, Neptune

Although Saturn was successfully detected in X-rays with XMM-Newton and Chandra (Ness et al. 2004a,b), its emission is caused by scattering of solar X-rays (Bhardwaj et al. 2005b). The same process was also suggested for the origin of the X-rays observed from its rings (Bhardwaj et al. 2005c). No evidence has yet been found for any other emission component at Saturn, like auroral X-ray emission, which could, like in Jupiter, contain a charge exchange emission component in addition to electron bremsstrahlung. This is consistent with estimates by Branduardi-Raymont et al. (2010), which indicate that any auroral X-ray emission would be below the sensitivity limit of current instrumentation. For Uranus and Neptune, the situation is even more challenging, because of their larger distance from the Sun and their smaller size. Branduardi-Raymont et al. (2010) concluded that in-situ observations would be the only feasible way to search for auroral X-ray emission from Uranus and Neptune. Nevertheless, it is likely that charge exchange takes place at these outer planets, though at a very low level due to the much lower solar wind flux.

3.6 Mercury

A very interesting case is Mercury, which, as the innermost planet, is exposed to the heaviest solar wind bombardment of all the planets. Solar wind sputtering, accompanied by photon– and electron-stimulated desorption, thermal vaporization and meteorid impact, creates a tenuous, surface-bounded exosphere, where the atoms and molecules, mainly H, He, Na, Mg, K, Ca move on collisionless trajectories until they return to the surface or escape from the planet (e.g. McClintock et al. 2009). In the latter case, they may get accelerated by solar radiation pressure to form an extended antisunward tail. As wide areas of Mercury's magnetosphere can be open to the solar wind, it is likely that charge exchange induced X-rays will be created in the sunward hemisphere of Mercury's exosphere.

With a maximum solar elongation of only $28.3°$, Mercury is by far too close to the Sun to be observed with imaging X-ray satellites from the Earth environment. The only possibility to study charge exchange induced X-rays at Mercury is to place an X-ray detector closer to the planet, ideally in an orbit around it. Such an opportunity will occur with BepiColombo, a joint mission between ESA and JAXA, which is planned to be launched in 2014 and to arrive at Mercury in 2020. BepiColombo comprises two orbiters. One of them, the Mercury Planetary Orbiter (MPO), will be equipped with an imaging X-ray spectrometer (MIXS). While the main goal for MIXS is to detect K and L shell fluorescence line emission in the top few microns of the surface in the 0.5–7.5 keV energy range (Fraser et al. 2010), this instrument can also be used for investigating other sources of X-ray emission. We are planning to utilize this unique opportunity for pioneering studies of charge exchange induced X-rays from Mercury's exosphere.

4 Challenges and outlook

Despite all the progress which has been made during the last few years in the investigation of charge exchange interactions, there are also major challenges. These challenges are present, in various forms, in all approaches, i.e., theoretical studies, laboratory studies, and astrophysical studies. Theoretical studies concentrate mainly on single electron capture, while multi-electron capture can be collectively as important or even more important (Ali et al. 2005). Another challenge for the development of spectral models for charge exchange is the requirement to predict the state-selective cross sections, as models which are based on approximations there may lead to erroneous conclusions and deductions of relevant parameters (Ali et al. 2010). For astrophysical studies of charge exchange, the main challenge is to achieve the necessary spectral resolution. In the following we demonstrate this for the comets, which provide the best case for the observational study of the charge exchange process.

The spectral resolution of X-ray CCDs is not sufficient to reconstruct the incident X-ray spectrum in an unambiguous way. This is especially true below ~ 0.5 keV, where the density of candidate emission lines is so high (Fig. 1) that their intensities cannot be determined in an unambiguous way without additional constraints. In order to avoid this problem, Bodewits et al. (2007) have developed a method where the relative intensities of all transitions of each ion are kept fixed according to emission cross sections which were independently determined for several collision velocities. With this method, it was possible to reduce the number of free parameters sufficiently to get physically meaningful results (Fig. 3).

However, this method relies on the fact that the velocity dependent emission cross sections are known well enough, which is not often the case. Even if it were, the fact that various velocity regions are sampled along the line of sight would require to know also the velocity distribution and to assign to each velocity dependent cross section a weight according to its contribution to the X-ray flux, individually along each line of sight. An additional complication arises from the fact that in the collisionally thick case, the initial population of solar wind ions is modified by charge exchange. O^{7+} ions, e.g., which result from O^{8+} ions after one charge exchange process, increase the initial population of solar wind O^{7+} ions. In order to take this effect correctly into account, it is again necessary to know the velocity evolution along the individual ion trajectories, in addition to the velocity dependent cross sections. While all this was considered in a pioneering study by Häberli et al. (1997), who calculated the plasma flow by a three-dimensional adaptive magnetohydrodynamic model, only a subset of the solar wind ions and de-excitation transitions was included, leading to a spectral prediction which was found to be inconsistent with the cometary spectra which were observed during the Rosat all-sky survey (Dennerl et al. 1997). This example demonstrates that cometary X-ray spectra provide a crucial test for our understanding of the physics of charge exchange and that higher spectral resolution, accompanied by sufficient spatial resolution, will be required in order to fully exploit the scientific potential contained in the cometary X-rays.

The best spectral resolution currently available in imaging X-ray satellites is achieved by gratings. Both Chandra and XMM-Newton are equipped with them. These gratings, however, are slitless, which implies that for extended sources the spectral resolution is degraded by the convolution of spatial and spectral structure along the dispersion direction. For only sightly extended sources, like Mars, this is no major problem: Figure 4 demonstrates that a resolution of ~ 4 eV can be achieved for Mars. Comets, however, are considerably more extended, often overfilling the field of view. In this case, a spectral deconvolution requires to know how the morphology of the comet changes with the energy. An energy dependence of the X-ray morphology is likely, because the cross sections for charge exchange are energy dependent. Thus, while slitless grating spectrometers offer the highest spectral resolution currently available, they are not the ideal instruments for extended sources like comets. In view of these difficulties, it appears that the promising potential of cometary X-rays for charge transfer studies has not yet been fully utilized.

Major progress is expected to be obtained with Astro-H (Takahashi et al. 2010), which is scheduled to be launched in 2014. This will be the first space mission which will perform X-ray observations with a microcalorimeter, providing a non-dispersive energy resolution of at least 7 eV in the energy range of 0.3–12 keV over a $\sim 2.9' \times 2.9'$ field of view, with an effective area of 160 cm^2 at 1 keV (Mitsuda et al. 2010). In contrast to the slitless grating instruments currently used on Chandra and XMM-Newton, the energy resolution will neither degrade nor get ambiguous for extended targets.

At the same time, the X-ray satellite eROSITA (Predehl et al. 2011) will be in the process of performing a total of eight all-sky surveys over the period of four years. This will then be followed by a phase of three years for pointed observations. With an effective area of ~ 1500 cm^2 at 1.5 keV, an (instantaneous) field of view with 1° diameter, an on-axis/average resolution of $\sim 15''/28''$, and a spectral resolution which is superior to XMM-Newton/EPIC and Chandra/ACIS, in particular at low energies, this satellite is ideally suited to study cometary X-ray emission over its full extent in unprecedented quality. eROSITA will become the first satellite to observe the X-ray sky from a halo orbit around the Sun-Earth L2 point, sufficiently far away from Earth to see an X-ray sky which is unaffected by charge exchange in the geocorona. This, together with repeated full sky coverage, may allow eROSITA to map heliospheric structures and their temporal variability, and thus separate them from diffuse X-ray emission coming from beyond the solar system, in particular from the Local Hot Bubble.

A most exciting mission for advanced studies of the physics of charge exchange would be ATHENA (Nandra 2011), which has taken the role of IXO as an L-class candidate mission in the ESA Cosmic Vision 2015–2025 program. ATHENA will consist of two identical X-ray telescopes with a focal length of 11 m, one equipped with a wide field imager (WFI), covering a $25' \times 25'$ field of view by 640×640 pixels with an energy resolution of ~ 50 eV at 0.5 keV, and the other one equipped with an X-ray calorimeter (XMS), covering a $2.4' \times 2.4'$ field of view by 32×32 pixels – with a resolution of 3 eV. Each telescope will have an effective area of ~ 6000 cm^2 at 1 keV and an angular resolution of 5–10$''$. Like eROSITA, ATHENA will observe from a halo orbit around L2. Its launch is currently foreseen for late 2022.

The imaging quality of XMS, concerning the spatial resolution and field of view, should be similar to that of the XMM-Newton / RGS image of Mars (Fig. 5), and the spectroscopic quality should be about twice as good as that which was obtained with RGS for Mars (Fig. 4) – but the sensitivity would be ~ 50 times higher. For the extended X-ray emission of comets, the XMS would completely solve the problem of the slitless grating spectrometers that spectral and spatial structures are mixed along the dispersion direction, and the combination of the WFI and the XMS, operated in parallel, would make it possible to keep the comet in the WFI, while part of it is slowly moving across the XMS for close spectral inspection. Thus it would be straightforward to disentangle temporal from spatial variations. In short, ATHENA is likely to provide a quantum leap in the study of charge exchange induced X-rays.

5 Summary and conclusions

What has started in 1996 with the (at that time) surprising discovery of cometary X-ray emission, has enriched X-ray astrophysics with new insights and novel applications. It has opened up a conceptual breakthrough for the understanding of previously unexplained properties of the soft X-ray background, and has caused a paradigm change concerning the origin of the soft diffuse X-ray emission, which was attributed before solely to the Local Hot Bubble. Evidence for charge exchange processes is now being found at various locations across the Universe. These investigations have just started and are still facing many challenges. With the forthcoming missions Astro-H, eROSITA and ATHENA, further investigations of "charge exchange across the Universe" are likely to have an exciting and bright future.

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