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X-ray probes of magnetospheric interactions with Jupiter's auroral zones, the Galilean satellites, and the Io plasma torus

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Abstract

Remote observations with the Chandra X-ray Observatory and the XMM-Newton Observatory have shown that the jovian system is a source of X-rays with a rich and complicated structure. The planet's polar auroral zones and its disk are both powerful sources of X-ray emission. Chandra observations revealed X-ray emission from the Io plasma torus and from the Galilean moons Io, Europa, and possibly Ganymede. The emission from the moons is due to bombardment of their surfaces by highly energetic magnetospheric protons, and oxygen and sulfur ions. These ions excite atoms in their surfaces leading to fluorescent X-ray emission lines. These lines are produced against an intense background continuum, including bremsstrahlung radiation from surface interactions of primary magnetospheric and secondary electrons. Although the X-ray emission from the Galilean moons is faint when observed from Earth orbit, an imaging X-ray spectrometer in orbit around one or more of these moons, operating from 200 eV to 8 keV with 150 eV energy resolution, would provide a detailed mapping of the elemental composition in their surfaces. Surface resolution of 40 m for small features could be achieved in a 100-km orbit around one moon while also remotely imaging surfaces of other moons and Jupiter's upper atmosphere at maximum regional resolutions of hundreds of kilometers. Due to its relatively more benign magnetospheric radiation environment, its intrinsic interest as the largest moon in the Solar System, and its mini-magnetosphere, Ganymede would be the ideal orbital location for long-term observational studies of the jovian system. Here we describe the physical processes leading to X-ray emission from the surfaces of Jupiter's moons and the properties required for the technique of imaging X-ray spectroscopy to map the elemental composition of their surfaces, as well as studies of the X-ray emission from the planet's aurora and disk and from the Io plasma torus.

Keywords: Instrumentation; Experimental techniques; Jupiter, magnetosphere; Io; Europa; Ganymede; Callisto; Aurorae; Abundances; Impact processes

1. Introduction

Besides our Sun, the Jupiter system is the most interesting, powerful and diverse source of X-rays within the Solar System. Observations have identified four distinct sources of X-ray emission: (1) the high-latitude auroral zones on Jupiter (Metzger et al., 1983; Waite et al., 1994; Gladstone et al., 2002); (2) the disk of Jupiter (Waite et al., 1997; Maurellis et al., 2000); (3) the Io plasma torus (IPT, Elsner et al., 2002); and (4) the Galilean satellites Io and Europa, with an indication of emission from Ganymede (Elsner et al., 2002). Although these X-ray emissions are faint when observed from Earth orbit, an imaging X-ray spectrometer

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on board a spacecraft moving within the jovian system (e.g., in orbit about the planet or the individual Galilean satellites) would provide a superb capability for unprecedented X-ray studies of Jupiter's auroral and disk X-ray emissions, the IPT X-ray emission, and through measurement of fluorescent line intensities, perhaps most importantly of all, the elemental composition of the surfaces of Jupiter's icy moons and of Io. Such studies can also provide a probe of magnetospheric plasma interactions with Jupiter's upper atmosphere and the Galilean moons.

All of the X-ray phenomena that result from magnetospheric processes could be studied with a Jupiter-based observing platform, which would have unprecedented temporal, spatial, and spectral coverage. Tremendous progress could be made in understanding the surface composition of the icy satellites, auroral processes, the global magnetospheric electrical circuits, and perhaps even the interior structure of Jupiter. In this paper we review what is presently known about the magnetospheric interactions leading to the observed X-ray emissions, and discuss what can be learned from a sensitive imaging X-ray spectrometer within the jovian system.

2. X-ray emission and scattering processes

A number of interactions among electrons, protons, ions, neutral atoms and electromagnetic fields lead to the production of X-rays (see the books by Tucker, 1975; Rybicki and Lightman, 1979). One of the simplest is the interaction between an electron and proton or ion leading to the emission of a photon. The electron begins and ends unbound to the heavy positively charged particle. This process is called bremsstrahlung and leads to broadband continuum emission. For sufficiently energetic electrons, the spectrum can peak in the X-ray band or at higher frequencies. The spiraling of a nonrelativistic electron in a magnetic field leads to cyclotron radiation at discrete harmonics of the cyclotron frequency. At higher electron energies the harmonic line emission spreads out forming a continuum; at relativistic energies this is referred to as synchrotron radiation. The shape of the X-ray spectrum can be altered by Compton scattering in which an X-ray scatters off an electron either losing energy, if the electron energy is less than the photon energy, or gaining energy, if the electron energy is greater than the photon energy. Recombination in which an ion captures a free electron produces a continuum spectrum with a sharp low energy cutoff at the binding energy of the atomic level involved. Recombination is the inverse process to photo-ionization in which a photon is absorbed by an atom or ion, kicking out an electron and increasing the charge state by one. If the ejected electron comes from an inner shell, one of the outer electrons will drop to the lower level causing either the ejection of a second (Auger) electron from an outer level or the emission of a fluorescent photon with energy equal to the energy difference between the two levels. When the ejected electron comes from the innermost energy level (the K shell), then for elements from carbon through iron, the energy of the fluorescent photon will lie in the X-ray band between 277 eV (for carbon) to 6.4 keV (for iron). Fluorescent emission can also occur when the outer electron drops into a level above the K shell (say the L shell), however for most of the elements of interest the energies of such transitions lie below the X-ray band. The L shell fluorescent lines for iron are at 705 and 718 eV, which is within the X-ray band of interest to us; however, the L shell fluorescent yield is much less than for the K shell.

Also important in the present context are interactions between ions and neutral atoms or other ions. In the process known as collisional ionization, an interaction between an energetic ion or electron with a neutral atom leads to the ejection of an electron from the atom. If the ejected electron is from the outermost energy level, as is most likely, a free electron will eventually recombine with the newly formed ion leading to the emission of a low energy photon typical of recombination. If the electron is from an inner energy level, it is likely that an electron from an outer level will fall to the inner level with the emission of a fluorescent photon, and eventually recombination to the outer lever will also occur. If the inner energy level is the K shell, then for carbon through iron, as above, the energy of the fluorescent line emission will fall in the band 277 eV to 6.4 keV. Collisional ionization can also occur between two ions, but the line energies will be different because the energy levels in the ion are somewhat different, depending on the degree of ionization, from those in the neutral atom. In the charge exchange process (cf. Cravens, 1997, 2002), the energetic ion captures an electron from the neutral atom, reducing the charge state of the incident ion by one but leaving it in an excited state. Subsequently this excited product ion de-excites and emits a fluorescent photon, or even two if the de-excitation occurs in two stages. If the excited product ion has a vacancy in the lowest energy level (K shell) then X-ray line emission can occur as already discussed.

All of these processes occur in the jovian environment. Which ones dominate depends on the relative cross-sections for the processes, and the particle energies, densities, and electromagnetic field strengths of the particular environment. Jupiter's auroral X-ray emission is attributed to charge-exchange between energetic ions and neutral atoms high in the polar atmosphere (cf. Bhardwaj and Gladstone, 2000, and references therein). X-ray emission from the Galilean moons may result from the energetic ions incident on their surfaces ionizing and exciting neutral surface atoms leading to fluorescent K-shell line emission (Elsner et al., 2002). A detailed understanding of the X-ray emissions from the jovian system requires detailed modeling of the complex interactions to be compared with high-quality X-ray spectra. We are presently engaging in construction of a detailed model for the X-ray emission from Jupiter's icy moons.