SOFT X-RAY INSTRUMENTATION FOR PLANETARY EXPLORATION: CURRENT STATUS AND FUTURE POTENTIAL

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1. Introduction

Each of the plasma processes governing the solar wind's interaction with planetary bodies generates diagnostic density structures. Proposed processes include ion pick-up, the Kelvin-Helmholtz instability, and magnetic reconnection. Determining the significance of each process to the loss of planetary atmospheres requires global imaging. Fortunately solar wind charge exchange (SWCX) operates throughout the regions of interest at solar system objects with atmospheres and exospheres including the moon, Earth, Mars, Venus, and Jupiter as well as comets. SWCX generates soft X-rays that can be used to image the characteristic density structures, so that planetary spacecraft with appropriate instrumentation can map out the plasma structures surrounding these bodies, delineating the locations of plasma boundaries such as ionopauses, magnetopauses, bow shocks, and wakes, determining when and where the plasma reaches the planetary atmospheres as a function of solar wind conditions, and identifying regions where sputtering occurs.

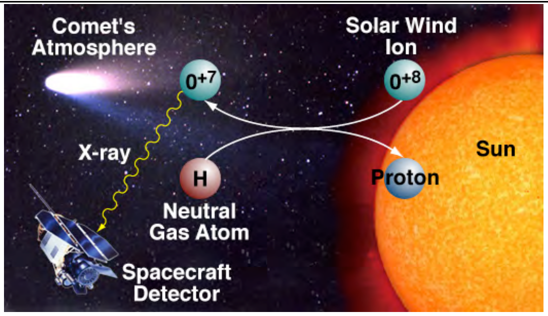

Figure 1 - Solar wind charge exchange soft X-ray emission mechanisms.

2. The SWCX Mechanism

In the mid-1990s observations of comet Hyakutake by the Roentgen Satellite, ROSAT, revealed unexpectedly strong soft X-ray emission [1]. This was a mystery at the time: very hot objects are normally required to produce X-rays, and comets are far too cold. However, shortly thereafter Cravens provided the explanation for this mysterious emission. Although comprised primarily of protons and helium, the solar wind also contains a small percentage (<1%) of high-charge-state heavy ions like C^{6+}, O^{7+}, and Fe^{13+}. Ionized in the solar corona, these species maintain their charge state as the solar wind flows outward through the solar system. When these solar wind ions encounter the high densities of neutral atoms close to a comet, they undergo charge exchange, basically "stealing" an electron from the cometary neutral atoms. The resulting heavy ion, which now has a charge state lower by one, ends up not in the ground state, but rather in an excited state. This excited state quickly relaxes, and in the process the product ions emit soft X-ray and EUV photons. This process is shown in **Figure 1**. Subsequently, we have learned that all comets are X-ray sources with luminosities as high as 1 GW and with the emission extending over hundreds of thousands of kilometers.

3. Science at Mars, Venus, Jupiter, and the Moon

The SWCX machanism, first discovered as discussed above at a comet, has myriad scientific applications for cometary studies, particularly locations of boundaries such as cometary bow shocks. However, scientific benefits also extend to many, indeed practically all, planetary bodies in the solar system.

For example, there are a host of possible processes for atmospheric loss at Mars and Venus. Observing the SWCX emission process near these bodies can discriminate between the diagnostic plasma density signatures/structures of each process. Examples include: (i) bow shock locations provide measures of exospheric densities, (ii) asymmetries in bow shock location depend on the rate of ion pick up, (iii) reconnection at remnant fields and between draped interplanetary magnetic field lines at the ionopause can rip off bubbles, and (iv) non-linear Kelvin-Helmholtz instabilities can rip off bubbles. Evaluating the relative importance of each process requires a global imaging perspective that single point measurements cannot provide.

At Jupiter, several X-ray observatories have reported powerful aurora in both the UV and the X-ray parts of the spectrum. Chandra observed X-ray emission from the Io Plasma Torus and from Saturn's rings. The auroral X-ray luminosity of Jupiter is about 1 GW and the emission originates in the polar cap region, sometimes with a 40-minute periodicity. The source of the auroral X-rays may be solar wind ions precipitating in the cusp or sulfur and oxygen ions in the outer magnetosphere that have been accelerated to energies of about 1 MeV/nucleon.

Our team recently reported ROSAT Position Sensitive Proportional Counter observations of soft X-ray emission from the solar wind-lunar interaction [2]. At the moon, SWCX soft X-ray emission reveals the global structure of the solar wind-lunar interaction and the lunar exospheric profile. For example, in the case of the moon, which has no large scale magnetic field, the plasma will, in general, strike the surface. However, above magnetic anomalies, such as Reiner Gamma, the solar wind may be deflected and not reach the surface. A soft X-ray imager will be able to determine how close to the lunar and other planetary surfaces the solar wind penetrates, providing answers to space weathering questions.

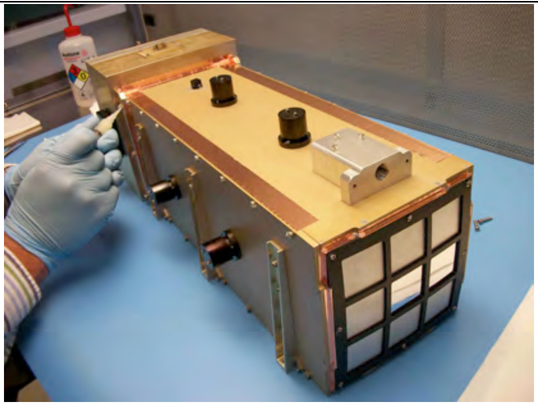

Figure 2 - A flight prototype wide field-of-view soft X-ray imager.

4. Prototype Wide Field-of-View Soft X-ray Imager

GSFC developed and flew the first wide-field-of-view soft X-ray imager suitable for planetary science on a Black Brant IX sounding rocket from White Sands Missile Range on December 12, 2012. The prototype, shown in **Figure 2**, has a mass of 7.7 kg, a volume of about 20,400 cm^3, and required 4.2 Watts power in its nominal operating mode [3,4]. The imager design accommodates nine 4 cm x 4 cm micropore reflectors (focusing elements for soft X-rays [5]). This technology demonstration imager successfully observed the soft X-ray background and conclusively showed that the generally brighter sources of planetary soft X-ray emission from the interaction between the solar wind and planetary bodies in the solar system can be imaged in soft X-rays.

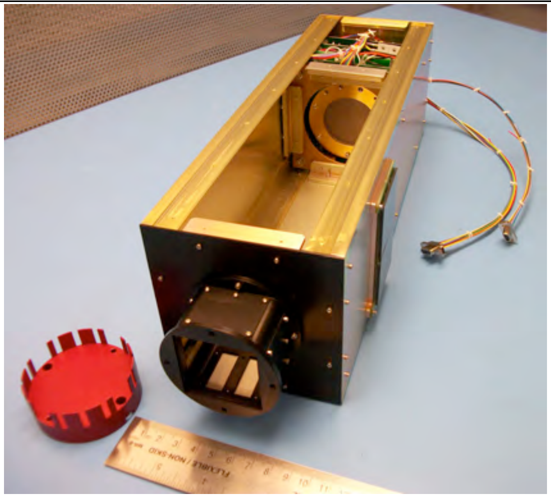

Figure 3 - A 3U CubeSat wide field-of-view (~5°x5°) soft X-ray imager.

Although the Black Brant rocket experienced "serious thrust anomalies" that saturated the accelerometers at 25 g during this launch (random vibration testing was done at 12.7 g) and caused the Sounding Rocket Program Office to suspend all Brant flights for a period, the prototype survived the rough ride and functioned nominally. In particular, the UV filters mounted on the micropore reflectors were perfectly intact when the instrument was recovered from the desert the morning after launch.

5. CubeSat Wide Field-of-View Soft X-ray Imager

Although the prototype flown had a larger envelope than a CubeSat, this flight experience suggested that a wide field-of-view soft X-ray imager could be miniaturized to fit, along with the necessary avionics, into a CubeSat envelope.

Figure 3 shows the integrated 3U CubeSat soft X-ray instrument with its electronics boards and detector plane (at the back). A planetary version of this CubeSat will require 6U to house additional necessary hardware such as thrusters, additional solar array capability, additional radiation shielding, etc. Through miniaturization, like this CubeSat, the planetary science benefits of soft X-ray imaging will be realized along with the cost-effectiveness of these small satellites on future planetary missions.

References: [1] Lisse et al. (1996) *Science,* 274, 205-209. [2] Collier et al. (2014) *JGR - Planets,* 119, doi: 10.1002/2014JE004628. [3] Thomas, N.E. et al. (2013) *Proc. of SPIE,* 8859, doi: 10.1117/12.2024438. [4] Collier, M.R. et al. (2012) *Astron. Nach., 333,* 4, 378-382, doi: 10.1002/asna.201211662. [5] Porter, F.S. et al. (2008) *Proc. of SPIE*, 7011, doi: 10.1117/12.790182.