Prospects for X-ray Astronomy from the Lunar Surface

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Summary

The next decade or two is likely to see a huge increase in the scientific endeavour associated with lunar exploration. In this paper we discuss the part that X-ray astronomy can play within this activity. An X-ray telescope on the lunar surface can make important scientific observations of the interactions of the solar wind with both lunar and terrestrial sources; the position of the Moon relative to the Earth makes the moon an ideal location for observing X-ray emission from the solar wind charge exchange (SWCX) process in the Earth’s magnetosheath. Compact and low-mass X-ray telescopes can be constructed that would be carried to the lunar surface by either manned missions or on automated soft landers. In both cases the X-ray telescope would be a small part of a much larger scientific payload.

2. Introduction

Previous speculations on the potential of the moon as a base for lunar X-ray observatories have tended to consider telescopes with ultra-large collecting areas (~100 m²) constructed within an existing lunar industrial infrastructure [7]. The low gravity, relatively negligible atmosphere, and availability of suitable raw materials making construction on the Moon, compared with Earth-launched, space-based solutions, perhaps a more cost effective method of achieving an order of magnitude or greater improvement in collecting area. It is not the purpose of this paper to further discuss such a scenario which depends on the uncertain political and financial landscape decades in the future. Rather, we consider the potential, and very practical, role of X-ray astronomy within the current climate of increased interest in the Moon by all the major space agencies in the world.
Lunar X-ray astronomy has a useful role to play in the immediate future of lunar exploration. X-ray telescopes can be constructed that are lightweight (a few kg), low power, and sensitive enough to make extremely useful scientific observations. Such telescopes can be carried to the lunar surface (or orbit) as a small part of much larger instrumental packages, either onboard automated soft landers or delivered by astronauts as part of the human exploration programmes. Within the context of NASA’s Global Exploration Strategy unveiled in 2006, NASA has already tendered submissions for study proposals of small science packages to be delivered by astronauts to the lunar surface; the Lunar Sortie Science Opportunities (LSSO) program. This is directly analogous to the Apollo Lunar Surface Experiment Packages (ALSEP) placed on the moon in the Apollo era. NASA/GSFC (PI M. Collier) in collaboration with the University of Leicester (UK) has proposed a soft X-ray telescope for the LSSO program.

3. Science goals for a lunar X-ray telescope

3.1 X-rays from the lunar atmosphere

The solar wind charge exchange (SWCX) mechanism has been recognised as a significant source of solar system X-ray emission for only the last decade. SWCX X-rays are produced when solar wind ions exchange electrons with neutral molecules or atoms during an impact. The solar wind ion is left in an excited state which decays with the emission of one or more photons. A typical reaction might be

\[ \text{O}^{q+} + \text{H} \rightarrow \text{O}^{q+*} + \text{H}^+ \]

If the ionisation state, q, is sufficiently large soft X-rays are produced when the ion de-excites. SWCX emission is produced from interactions of the solar wind with planetary atmospheres [4], [5], comets [3], [11], geocoronal hydrogen [16], and interstellar neutral atoms inside of the heliosphere and at the heliospheric boundary at the edge of the solar system [15]. Diffuse emission from the latter two sources is now recognised as a significant source of soft X-ray emission contributing to the all-sky survey undertaken by ROSAT in the 1990’s [2], [9]. Referred to as ‘long-term enhancements’ at the time, this SWCX contribution to the X-ray surface brightness was identified by its temporal signature and partially removed by empirical analysis.

The moon has a tenuous atmosphere with a surface density, \(n_0\), of about \(10^5\) cm\(^{-3}\) and an exponential scale height, L, of about 40 km [21]. The atmosphere is generated by outgassing through radioactive decay processes in the lunar crust and sputtering from the surface through particle and photon impacts. The Moon lacks a large-scale dipolar magnetic field like the Earth’s and consequently the solar
wind impacts the atmosphere directly. SWCX emission from this interaction will be the dominate source of X-rays produced within the lunar atmosphere. X-rays can also be generated by elastic and fluorescent scattering of solar X-rays from a gas, however, the cross-sections for these interactions are very small compared to those for SWCX and the column density of the atmosphere is not sufficient to produce significant X-ray intensities via these mechanisms.

The SWCX X-ray flux, I, can be estimated using

\[ 4 \pi I = \alpha \Phi_{sw} n_0 L f \]

where \( \Phi_{sw} \) is the solar wind flux which is typically \( \sim 3 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \). The factor, \( \alpha \sim 6 \times 10^{-16} \text{ eV cm}^{-2} \), incorporates the possible transitions and their weighted cross-sections [8]. The value of \( \alpha \) is not very sensitive to the target species for high charge state projectile ions as in the solar wind. The viewing geometry is represented by the factor, \( f \), which will vary between 1 for radial and \( \sim 5 \) for limb viewing. This gives an X-ray flux (for \( f \sim 1-5 \)) of

\[ I \sim (6-30) \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \]

which compares with the typical fluxes of \( \sim 6 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) from diffuse interstellar sources and \( \sim 8 \text{ keV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \) from terrestrial sources.

### 3.2 Solar System X-ray emission

The magnetosheath lies between the bowshock formed by interaction of the solar wind with the Earth’s magnetosphere and the region where the Earth’s magnetic field dominates. It lies at a radius of approximately 11 to 13 \( R_E \) in the Earth-Sun direction. SWCX X-ray line emission has been detected from this region by XMM-Newton [20], and Suzaku [6].

The XMM spectrum (from the EPIC-MOS detector [22]) is shown in Figure 1. A detector with CCD resolution or better (EPIC-MOS has a FWHM resolution, \( E/\Delta E \sim 70 \text{ eV at 1 keV} \)) can resolve the individual lines and so provide information on the solar wind composition. Simulations show that the brightest part of the magnetosheath in X-rays may be the cusp region where solar plasma has direct access to the upper atmosphere [16].
Figure 1 - EPIC-MOS spectra (red and black) of observations within the Hubble Deep Field North [20]. The SWCX component (in green) is an enhancement of the spectrum in black. Spectral lines from C, O, Fe, Ne, and Mg solar wind ions are clearly resolved.

Comparisons of the X-ray emission observed by ROSAT (observing from below the magnetosheath in low-Earth orbit) and the solar wind particle flux show a strong correlation (Figure 2). Thus, the X-ray flux from SWCX provides a proxy for the solar wind flux. Furthermore, SWCX observations during periods of intense solar activity when the magnetopause is frequently pushed close to the Earth could provide real-time indications of the locations of the bowshock, cusps and magnetosheath, important for understanding geomagnetic storms which are of great scientific interest, but also pose significant hazards for spacecraft.

Figure 2 - Correlation of the strength of the solar wind and the soft X-ray emission as seen by ROSAT.
The constraints imposed by the observing programmes and orbits of current free-flying instruments restrict the potential of studying the solar wind/magnetosphere interaction via SWCX in any systematic way using conventional X-ray observatories. The advantage of a lunar based observatory lies in the particular geometry of the moon’s orbit with respect to the magnetosheath. As illustrated in Figure 3, a lunar observatory could be positioned to systematically scan the region each lunar day (i.e. terrestrial month).

![Figure 3](image.png)

**Figure 3** - Field of view of a lunar observatory with a fixed look angle. At this position the observatory will sweep past the magnetosheath each month providing a systematic mapping and monitoring of the region.

### 3.3 Diffuse emission from the interstellar medium

All of the current and planned X-ray observatories are either in low Earth-orbit or in elliptical orbits which spend only a short time outside of the Earth’s magnetosheath. Thus, their view of the diffuse soft X-ray emission from the interstellar medium (ISM) is potentially contaminated by SWCX from the magnetosheath. A lunar X-ray telescope will have an unrestricted view angle outside of this region for much of the lunar orbit and be able to achieve much longer exposures on these directions than are currently achievable with the current generation of free-flying spacecraft. SWCX emission is also expected, however, from the interplanetary medium and heliospheric boundary. This can be decoupled from the non-variant contribution of the ISM by correlation with solar wind activity.
3.4 Monitoring of extra-solar system objects

There is no technical or scientific imperative for placing an X-ray telescope designed to observe discrete extra-solar system objects on the lunar surface as opposed to operating on a free-flying spacecraft; a case can perhaps be made for future ultra-large arrays (~100 m\(^2\) or larger). A lunar X-ray instrument whose sole science goals were extra-solar system astrophysics would probably have difficulties being funded within a competitive process. Nevertheless, there are very important regions of discovery space that can practically be explored by small X-ray telescopes and the added value of a lunar telescope capable of making such observations should not be understated. In particular, wide area monitoring of the sky in X-rays is currently a largely unexplored region of high-energy time domain astrophysics. A lunar telescope could usefully contribute to the current and planned space-based missions in this field.

The optimal targets for a wide area X-ray monitor are phenomena with a low, and unpredictable, duty-cycle but a large dynamic range. Such phenomena are difficult to study with the small field-of-view observatories (e.g. ROSAT, XMM-Newton and Chandra) that have provided astronomers with the bulk of their soft X-ray data over the last two decades. Two potential areas of research that are largely unexplored will be considered here for example purposes. These are stellar captures by super-massive black holes (SMBHs), [14], [19], and so-called “super-flares” in isolated solar-like stars [18].

Stellar captures are occasional events which occur in the dense nuclei of galaxies containing an SMBH. The tidal disruption of a passing star by an SMBH forms a temporary accretion flow that can fuel a massive increase of the soft-X-ray luminosity, lasting for several weeks or months, of an otherwise X-ray dim galaxy. The duty cycle, which depends on the density gradient within the galaxy and the mass of the SMBH, is predicted to be between ~10\(^4\) and ~10\(^5\) years [12]. Only a handful of such events have so far been detected by chance. The frequency and luminosity function of a large sample would provide a strong constraint on the mass distribution of SMBHs and their evolutionary relationship with their host galaxies. Sensitivity calculations for the LOBSTER all-sky monitor concept (see Section 4) suggest that around a few times ~10\(^6\) possible SMBH containing galaxies can be monitored per year leading to potentially 100s of detected stellar capture events over the mission lifetime.

Equally rare, in terms of observational reports, are the so-called stellar super flares. These are solar-type stars showing a sudden optical brightening equivalent to a luminosity of ~10\(^{35}\) erg s\(^{-1}\) compared with a quiescent solar optical luminosity of 10\(^{33}\) erg s\(^{-1}\) [18]. Two examples of super-flares have also been detected in the X-ray band, by EXOSAT [10] and ROSAT [17], each of which was also around 100 times the quiescent X-ray luminosity of their respective parent stars. There is
no evidence for such flares from the sun, either by optical brightening or extreme aural activity from enhanced X-ray fluxes, in historical records dating back thousands of years.

One suggested explanation for super-flares on solar-like stars is magnetic reconnection between the magnetic fields of a star and a close-in, “hot Jupiter” [17]. This mechanism is analogous to the explanation for similar events observed in RS CVn binaries. This would explain why the Sun does not appear to exhibit super-flares because it lacks such a companion. If confirmed, the detection of super-flare events would therefore be an indirect method of identifying close-in gas giant planets, however, none of the observed super-flare stars have been found to have hot Jupiter companions in the radial velocity surveys, so the phenomenon remains a mystery.

4. Design considerations of a lunar X-ray telescope

4.1 Mass and power budget

In most scenarios a lunar X-ray telescope will have to meet fairly tight, but reachable, mass and power constraints; the budget for the LSSO experiment proposal is around 40 kg in mass and 20-30 W in power. The science goals for studying SWCX require good energy resolution at soft X-rays in order to resolve the line emission (see Figure 1) which would point towards CCDs or Solid State Detectors (Si(Li)) for the detectors. Large area CCDs are mature devices, central to the detector systems of most current X-ray missions and experience here shows that the telescope and associated electronics can comfortably be brought within this mass budget.

Both devices require cooling to ~100 K for optimum spectral performance. For an actively cooled system this would require about 20W (2W in standby) power, however, a telescope operated during lunar night could rely on passive cooling. In fact, as Figure 3 illustrates, this is precisely when such a telescope located to scan the magnetosheath would operate. The choice of suitable power supplies for a lunar experiment is, at this time, as much a political issue as a technical one. The ALSEP experiments in each Apollo mission were powered by a common radio-isotopic thermoelectric generator (RTG) which produced 70 watts; the heat source was radioactive plutonium. The political question mark concerning the use of radioactive energy sources may, possibly, preclude the use of an RTG, in which case the telescope would be powered by a solar-cell/battery system with a corresponding increase in overall mass and a reduced duty cycle.
4.2 Instrument design

As previously discussed, solid state devices offer the energy resolving power sufficient to isolate the line emission from individual solar ion species. For a telescope whose sole science goal was the study of SWCX emission, spatial resolution is not essential; the emission can be studied through its spectral and time-dependent properties. In this case a simple collimator would be sufficient for defining the field-of-view (fov) and background reduction. The spatial definition offered by small pixel CCDs would be redundant in such a telescope.

For a lunar base SWCX monitor, extra-solar observations would provide added scientific value, but require good spatial resolution for source identification necessitating the use of focussing optics. Appropriate low mass, compact imaging optics can be provided by spherically slumped microchannel plate arrays (Figure 4) which have shown relatively good X-ray focussing properties (~1.5 arcminute FWHM) [1]. This lobster-eye lens (named after the construction of the crustacean eye) has been proposed as the optical system for the LOBSTER ASM concept [13].

![Figure 4 - Basic principle of X-ray focusing using a square pore, spherically slumped microchannel plate.](image)

The telescope grasp (defined as field of view times the effective area) and the compactness of the system depend on the chosen radius of curvature of the slumped optic. Current designs for the LOBSTER optics being developed at the University of Leicester are optimised towards its primary science goal as an all-sky monitor; the chosen radius of curvature, $R = 75$ cm (focal length, $R/2 = 37.5$ cm), gives a large fov $30^\circ \times 30^\circ$ in a very compact form. Several such modules can be combined to give simultaneous coverage of a large fraction of the sky.

For a lunar X-ray telescope, the optical design can be altered to optimise sensitivity whilst still maintaining a useful fov and compactness. Figure 5 shows
theoretical effective area curves for an iridium-coated glass MCP optic of varying focal length. A focal length of 50 cm would significantly increase the effective area whilst keeping the optical system a practical size for a lunar telescope. The field of view of this optic would be a useful 9\(^\circ\) x 9\(^\circ\) for monitoring serendipitous extra-solar objects. The telescope’s grasp would be comparable to one of the EPIC-MOS cameras on XMM-Newton which have an effective area of ~500 cm\(^2\) at 1 keV and a fov of 30 arcminutes in diameter. An X-ray telescope attached to a lander on the far side of the moon where the Earth’s magnetosheath is unobservable could be constructed closer to the LOBSTER configuration.

The detector array should preferably follow the same radius of curvature as the optic. This can be achieved to an approximation by using side-butttable CCDs aligned on a curved plane.

![Figure 5 - Effective area curves for a slumped microchannel plane optic constructed of Iridium coated glass. Optics with three focal lengths (f = 37.5, 50 and 100 cm) and channel aspect ratios (L:D) are shown.](image)

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