SWCX Contribution to the Soft X-Ray Background Using X-LEAP Data

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1. MW Hot Gas and SWCX in Soft X-Ray Background
2. Complex Nature of SWCX Emission
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1. MW Hot Gas and SWCX in Soft X-ray Background

**MW Hot Gas (T > 10^6 K) Emission:**

- **Thermal Emission:** continuum (Bremsstrahlung)
- **Line Emissions:** O VII, O VIII, and Fe-L lines (0.56, 0.65, 0.7-1.0 keV; collisional ionization)
- **Coverage:** whole sky; faint

**SWCX Emission:**

- **Highly-Charged Ions:** O7+, O8+, and Fe+;
- **Line Emissions:** O VII, O VIII, and Fe-L lines (SWCX)
- **Coverage:** Whole sky
- **Nature:** Complicated
2. Complex nature in SWCX emission — Regions & Variations

**Region: Earth’s Exosphere (H & He)**

- **Variability**: Varies over days; sensitive to SW flux (e.g., Cravens 97; Freyberg 98)

**Region: Within the Heliopause (Neutral ISM)**

- **Variability**: Varies over years with lower amplitude; latitude-dependence expected;
3. The XMM-Newton Line Emission Analysis Program (X-LEAP)

**Need:** Requires extensive, long-term line emission data in soft X-rays

**Opportunity – MOS/XMM-NEWTON:** 1. > 22 years; 2. deep observations with large FOV.

**Goal:** To study variations in SWCX & the MW hot gas emission, using all usable MOS/XMM images

**Method:**

**Dataset:**
- **5470 measurements** (~3% sky)
- Largest & machine-readable (X-LEAP I)
- Long exposure (~ 20 ks) & Low contaminations
4.1. Long-Term & Spatial Variations Seen in X-LEAP data

- Highly correlates with solar activity
- Contributes \( \sim 30\% \) to the observed intensity in average
- Includes both \( I_{\text{helio}, \text{SWCX}} \) and \( I_{\text{mag}, \text{SWCX}} \)

- \( \text{O VII} \) intensities are higher at high latitudes
- Varying solar wind properties at different latitudes
4.2.0. SWCX Emission Intensity

The X-ray flux in a given spectral line:

\[ I_{SWCX} = \frac{1}{4\pi} \int_0^s n_M(s) n_{Xq^+}(s) V(s) \sigma_{M,Xq^+}(V) Y_{Xq^+,j}(V) \, ds \]

(Cravens+ 97)

Assume constant neutral gas density:

\[ I_{OVII,SWCX} \propto n_{O^{7+}} v_{O^{7+}} \] (O7+ flux) at where the CX happens

**SWICS/ACE:**

- Measures SW ion properties at L1 (e.g. vH+, nH+, HetoO, vC5+, etc.)
- Delay time (τ): ~ 1 h to exosphere; >1 year to heliopause
- Less reliable ion data after 2012, except H+ measurements
4.2. Correlations between Long-term SWCX and SW ion data

Most linearly correlated to He\textsuperscript{2+} number density

nHe\textsuperscript{2+} shows stronger correlation than O\textsuperscript{7+} flux
4.2. Correlations between Long-term SWCX and SW ion data

- Cumulative fraction of SWCX emission (red)
- ~80% SWCX <20 au; delay time < 3 months
- No obvious time-delay between X-ray and ACE data
4.3.0. Seeing Short-Term Variations after Minimizing MW Contribution

- MW hot gas emission
- $I_{\text{obs. O VII}}$ vs. O7+ flux ($t - 1$ h)?

Remove MW emission:
- Intensity differences in observational pairs $< 2^\circ$

$$
\Delta I_{\text{obs, O VII}}(t_1, t_2)
$$

- $A * \Delta \text{Flux} (t_1 - \tau_{\text{mag}}; t2 - \tau_{\text{mag}})$ differences in mag
- $B * \Delta \text{smoothed Flux} (t_1 - \tau_{\text{helio}}; t2 - \tau_{\text{helio}})$ differences in helio SWCX

- MW emission $< 2^\circ$ are considered negligible
  (Kaaret+ 20; Qu+ 24)
4.3. Short-Term Variation Seen in X-LEAP data

\[ \Delta I_{\text{obs, O VII}}(t_1, t_2) \]

\[ A \ast \Delta \text{Flux (} t_1 - 1 \text{ h; } t_2 - 1 \text{h)} \]

\[ B \ast \Delta \text{smoothed Flux (} t_1 - \tau_{\text{helio}}; t_2 - \tau_{\text{helio}}) \]

differences in mag SWCX
differences in helio SWCX

- Linear correlation between X-ray and O7+ flux differences
- Residuals

- delay time \( \sim 2 \) hours from CCF; expected \( > 1 \)h
- 2h interval?
5. An Empirical Model to Estimate SWCX Emissions (Before 2012)

\[ I_{\text{obs, O VII}}(t) = A \times O^{7+} \left(t - \tau_{\text{mag}}\right) + B \times n_{\text{He}^{2+}} \left(t - \tau_{\text{helio}}; \sigma = 6 \text{ m}\right) + \text{Const.} \]

- An estimation of the SWCX strength at certain \( t \)

Future Improvements:
- Spatial variations (SW ion and neutral gas distributions across latitudes)
- \( \sigma_{H, O^{7+}}(V) \)
Thank you 😊
SWICS:
- Installed on ACE satellite
- Measures SW ion properties at L1 (e.g. H+ flux)

- O VII line intensity increases with proton flux
- Evidence of short-term variations due to $I_{\text{mag}, \text{SWCX}}$

Observation sets pointing at same directions

Pan+ 24
Goal: To study the short/long-term & spatial variations in SWCX using all usable MOS images

Method:

1. XMM-NEWTON X-ray Telescope: 1. deep observations with large FOV; 2. > 22 years

Need: requires extensive, long-term soft X-ray line emission data

- 5418 measurements (~3% sky)
- Long exposure (~20 ks) & Low contaminations
- Machine-readable

O VII Intensity Measurements
Supplementary Materials

\[ F_{O^7+} = n_{He} v_{He} \frac{n_O}{n_{He}} \frac{n_{O^7+}}{n_O} \]

smoothed \( f(t, \sigma = 6 \text{ m}) = \text{np.median} (f[t - \sigma, t + \sigma]) \)
Solar wind ions can capture electrons from neutral atoms, producing X-ray photons (SWCX).

\[
\text{e.g.} \quad O^{+7} + H \rightarrow O^{+6}^* + H^+ \\
\rightarrow O^{+6} + H^+ + h\nu
\]

*Local Hot Bubble (I_{LHB})*

\[ T \sim 10^6 \text{ K} \]
\[ n_e = 4 \times 10^{-3} \text{ cm}^{-3} \]

(e.g., Liu+ 16; Yeung+ 23)

**Supplementary Materials**
Supplementary Materials

Ulysses Spacecraft (1990-2009)
SWICS/Ulysses

Kuntz 2019