X-ray spectrometry with Exosat and beyond

Johan Bleeker
SRON/Utrecht University

EXOSAT-Reunion, ESAC May 25, 2018
The grass roots at Utrecht

Atlas of the solar spectrum: $\lambda 3612 - \lambda 8770, \lambda 3332 - \lambda 3637$

Initiative by Marcel Minnaert

- 1936: ~ 100 photographic plates taken at Mount Wilson Observatory
- 1940: Utrecht Photometric Atlas of the solar spectrum (Minnaert et al)
- 1952: Solar atmosphere temperature model (de Jager 1952)
- 1966: Solar abundances from The Solar Spectrum (Moore et al)
Mid 1960’s: Monochromatic XUV-images of the Sun

X-ray lens employing diffraction: Fresnel zone plate

Principle: zone partition of spherical wavefront → block even/odd zones

\[
\left( \frac{1}{\rho} + \frac{1}{r_0} \right) = \frac{n\lambda}{r_n^2}
\]

Plane wave → \( r_n = \sqrt{n r_0 \lambda} \)

Differentiation \( r_0 = f_1 \) →

\[
f_1 = \frac{2 r_n \Delta r_n}{\lambda}
\]

**Focal length** \( f_1 \) \( (\lambda = 5\text{nm}, \Delta r_N = 1\mu\text{m}, r_N = 1\text{mm}) : 40 \text{ cm} \)
Mid 1960s: Q-monochromatic XUV-images of the Sun
X-ray lense employing diffraction: Fresnel zone plate

Requirement: transparent zones completely open, width 1-2 μm → radial support
First successful trials with electron-optical imaging:

Non-apodized zone plate manufactured by electron-optics early 1960's

Problem: FOV of the available system too small for the production of larger ring shaped zone plates with a sufficiently large opaque central section to avoid distortion of the image by zero-order radiation from the sun.
Mid 1960s: Q-monochromatic XUV-images of the Sun

X-ray lens employing diffraction: Fresnel zone plate

Photolithography:
Employment of a holographic method that produced a zone pattern resulting from interference of two coherent spherical wave fronts generated by a beam-split Cd-He laser.

1967: Successful sun stabilized Aerobee rocket experiment

4 Zone plates of 50 metallic rings
f = 40 cm, outer diam. 0.90–3.06 mm

→ Solar Q-monochromatic images in Si X, Fe XI, He II and He I lines

▲ Sun in Si X at 5.1 nm
TGS (500 lines mm\(^{-1}\) and 1000 lines mm\(^{-1}\)) on EXOSAT

\[ \Delta \lambda \approx 1.3 \text{ Å} \]

\[ \Delta \lambda \approx 2.5 \text{ Å} \]
TGS: Observational targets

Distinguishing feature from previous instruments:
Unprecedented dynamic range over the soft-X and EUV band (8 - 400 A), with a superior combination of sensitivity and spectral resolution in the XUV band (50 - 400 A).

Priority targets:
- Hot photospheres of nearby white dwarfs
  TGS covers the full XUV spectrum between the intrinsic short wavelength cut-off of the stellar spectrum (at \(\approx 50\) A) and the cut-off in the EUV band due to interstellar absorption.

- Hot coronae of nearby late-type stars
  TGS resolves (\(\Delta \lambda \approx 3\) A) ionic coronal emission lines over a wide temperature range \(\rightarrow\) temperature and emission measure distribution of the hot stellar coronal plasma.
TGS-spectroscopy of hot WDs: Sirius B, the WD star closest to the earth

The Sirius system, brightest star in the night sky ($m_v +1.42$)

Binary: Sirius A (MS A1) + Sirius B (DA white dwarf)
Distance: 2.6 pc, 8.6 ly (Hipparcos)
Solar units: $M_{\text{Sirius A}} \approx 2 M_\odot$, $L_{\text{Sirius A}} = 25 L_\odot$

Discovery of soft X-ray emission by ANS (Mewe et al, 1975)

Interpretation:
1. Miniature corona DA dwarf (Hearn and Mewe, 1976)
   Corona of an exotic kind: scale height $\approx 100$ cm,
   $L_X > 5L_{\text{phot}}$ (Martin et al., 1982)
2. Hot pure-H-Photosphere (Shipman, 1976)

EXOSAT TGS $\rightarrow$ XUV spectrum $\rightarrow$ atmospheric parameters
Full EM spectral data $\rightarrow$ photospheric parameters + $R_{\text{WD}}$
TGS-spectroscopy of hot WDs: Sirius B, the WD star closest to the earth

EXOSAT spectroscopy, 99% confidence limits:

\[ T_e = 24,500 - 26,000 \]

\[ R/R_\odot = 0.008 - 0.012 \]

\[ \log g = 8.3 - 8.7 \]

\[ \text{He/H} < 2.10^{-5} \]

Parameter set for a consistent model covering the full EM spectrum: optical, UV, EUV, soft-X:

\[ T_e = 25,000 \pm 500 \text{ K} \]

\[ R/R_\odot = 0.0079 - 0.0085 \]

from \[ M/M_\odot = 1.053 \pm 0.028 \]

\[ \log g = 8.53 - 8.73 \ (\approx 400,000 g_{\text{earth}}) \]

\[ \text{He/H} < 2.10^{-5} \]

\[ N_H = (1.1 - 5.0) \times 10^{18} \text{ cm}^{-2} \]
TGS-spectroscopy of hot WDs: HZ 43, a very young luminous hot WD!


Interpretation: 1. High $T_e$ radiation field prevents He from quick downward diffusion due to large gravity?
2. Accretion of interstellar He onto DA photosphere?

Parameter set for a model consistent with the full EM spectrum of HZ 43:

- $T_e = 45,000 – 54,000$ K
- $R/R_\odot = 0.0140 – 0.0165$
- log $g = 7.8 – 8.4$
- He/H < 1.0 x 10^-5

(Paerels et al, 1986a)
(Heise et al 1988)
TGS-spectroscopy of hot WDs: Feige 24, a surprising photosphere!

- No fit with He II Ly-edge possible (Paerels et al, 1986b)
- No improvement by adding traces of C, N and Si (Paerels, et al, 1986b)
- Improved fit with heavier trace elements up to Ca consistent with IUE abundances (Vennes et al, 1989)
- A later deep 31 hour IUE exposure indicated Fe/H = (5-10).10^-6
  → A complex of hundreds of Fe IV, FeV and FeVI resonance lines may be causing the Feige XUV deficiency. The relatively high Fe-abundance significantly exceeds the prediction of selective radiation pressure models (Vennes et al 1992)
Hot Coronal Plasma: X-ray line spectra for cosmic abundance

First high resolution X-ray spectrum of the corona of Capella taken with the 1000 l/mm OGS on the Einstein Observatory (Mewe et al, 1982). The soft X-ray emission was discovered in 1975 by Mewe et al (ANS) and Catura et al (rocket flight).
Coronal activity in three late type stars: DEM distributions (TGS 1000 l/mm R \sim 3\lambda)


**Spectral fits:**
- T1, T2: 2 temperatures
- P : Polynomial
- WS: Multi-thermal

**Conclusion:**
- Bimodal temperature intervals centered on:
  - 5 MK and 25 MK (Cap, \sigma^2CrB)
  - 0.6 Mk and 3 MK (Procyon)
Post-EXOSAT generation grating spectrometers

Chandra LETGS/HETGS

Transmission grating

"Normal" incidence

\[ m \lambda = d(\sin \theta - \sin \chi) \]

\[ \Delta \chi \to \Delta \theta \to \Delta \lambda = \frac{d \cos \theta \Delta \theta}{m} \]

\[ \frac{\lambda}{\Delta \lambda} = \frac{\theta}{\Delta \theta} \]

XMM-Newton RGS

Reflection grating

"Grazing" incidence

\[ m \lambda = d(\cos \beta - \cos \alpha) \]

\[ \Delta \alpha \to \Delta \lambda = \frac{d \sin \alpha \Delta \alpha}{m} \]

\[ \frac{\lambda}{\Delta \lambda} = \frac{\cos \alpha - \cos \beta}{\sin \alpha \Delta \alpha} \]

\[ \Delta \theta \to \Delta \lambda = \frac{d \sin \alpha}{m} \]

\[ \rho = \frac{d \sin \alpha}{\sin \alpha} \quad (p, \text{ ruling density}) \]

180 SiC plates (10 x 20 cm)

average line density 645 l/mm

Ø 110 cm
1000 l/mm
HR spectroscopy with Chandra LETGS, plasma density diagnostics with He-like triplets

LETGS 2 -180 A
Capella: Blow-up Fe complex

Plasma electron density $n_e$ from the triplet f/i ratio of the He-like ion

Capella OVII: $n_e = 3.10^9$, NVI: $7.10^9$, CV = $3.10^9$
Procyon OVII: $n_e = 2.10^9$, NVI: $9.10^9$, CV < $10^9$

- Electron density values typical for solar active regions
- No densities as high as in solar flares
- Flux generated in Magnetic Loops: filling factor exceeds solar >10
From Cooling Flows to Cool Cores in galaxy clusters.

Characteristically: temperatures $< T_{\text{max}}/3$ missing (Peterson & Fabian, 2006)

Abell 1835 (Chandra)
SNR shocks
The magnificent case of 1E0102-73 in the Small Magellanic Cloud
Energy-dispersive HR-spectroscopy: the Microcalorimeter on Hitomi

Perseus Cluster Core: Hot winds and turbulence
(Hitomi collaboration, Nature, 2016, 535, 117)
Perseus Cluster Core:
He-like and H-like Sulpher
1 eV energy bins

Perseus Core S−XV and S−XVI

Counts/(sec keV)

S XVI Ly-α

S XV He-α triplet

(f) (i) (r)

Energy (keV)
Perseus cluster core:
He-like Iron complex, 2 eV energy bins
hot gas turbulent motion \( \leq 164 \text{ km/sec} \)

Hitomi collaboration
Nature, 2016, 535, 117