Diffuse X-ray Emission in the Milky Way

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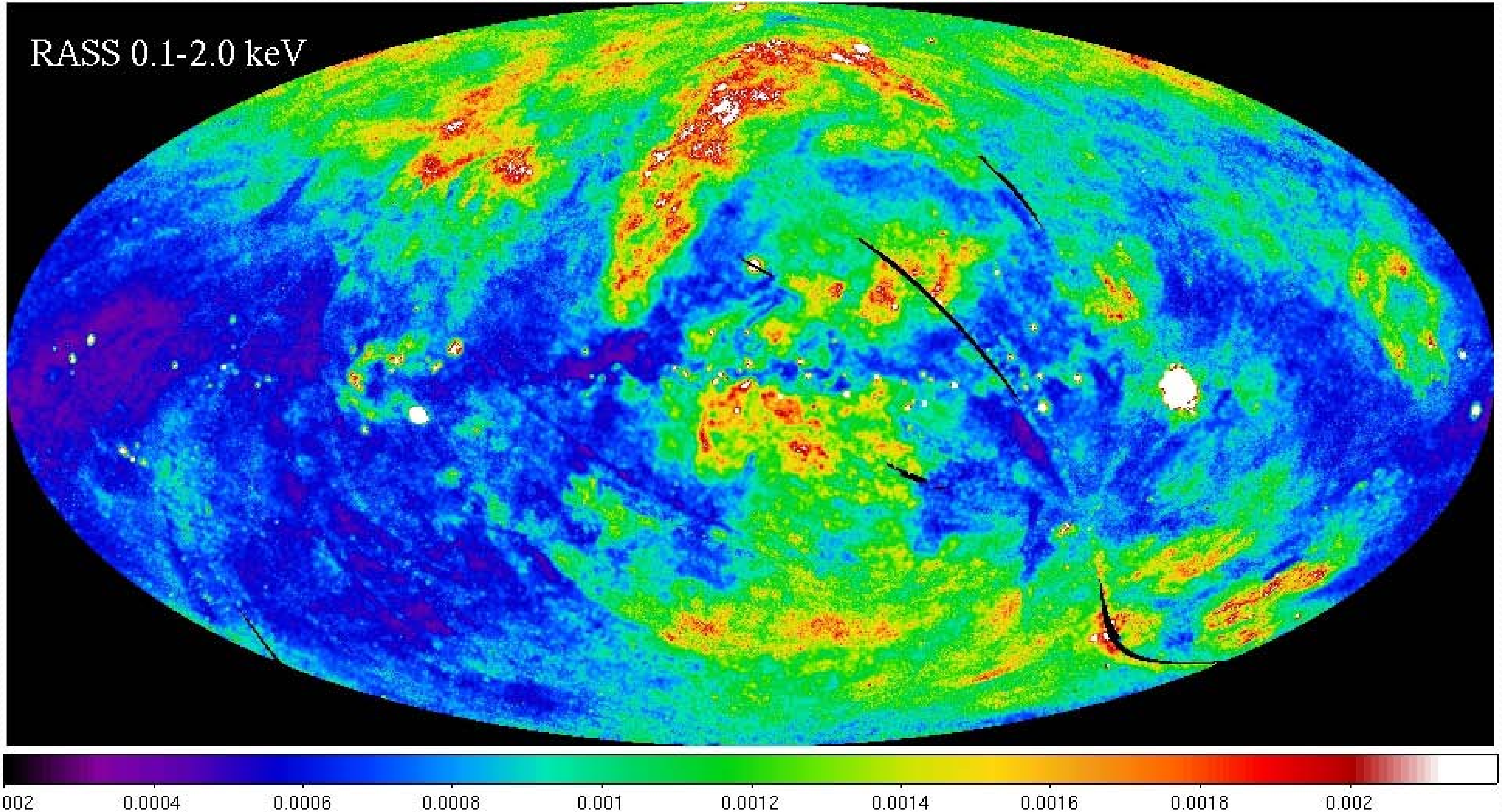
Our understanding of the diffuse X-ray emission from the Milky Way has evolved extensively from when it was first observed in the 1960's, and its origin is still the subject of debate as much now as ever. This presentation will provide an overview of that evolution, the various emission components, emission mechanisms, an assessment of the current state of the field, and implications for eROSITA.

And now for something completely different
eROSITA is a great observatory for studying the diffuse X-ray sky


RASS 0.1-2.0 keV
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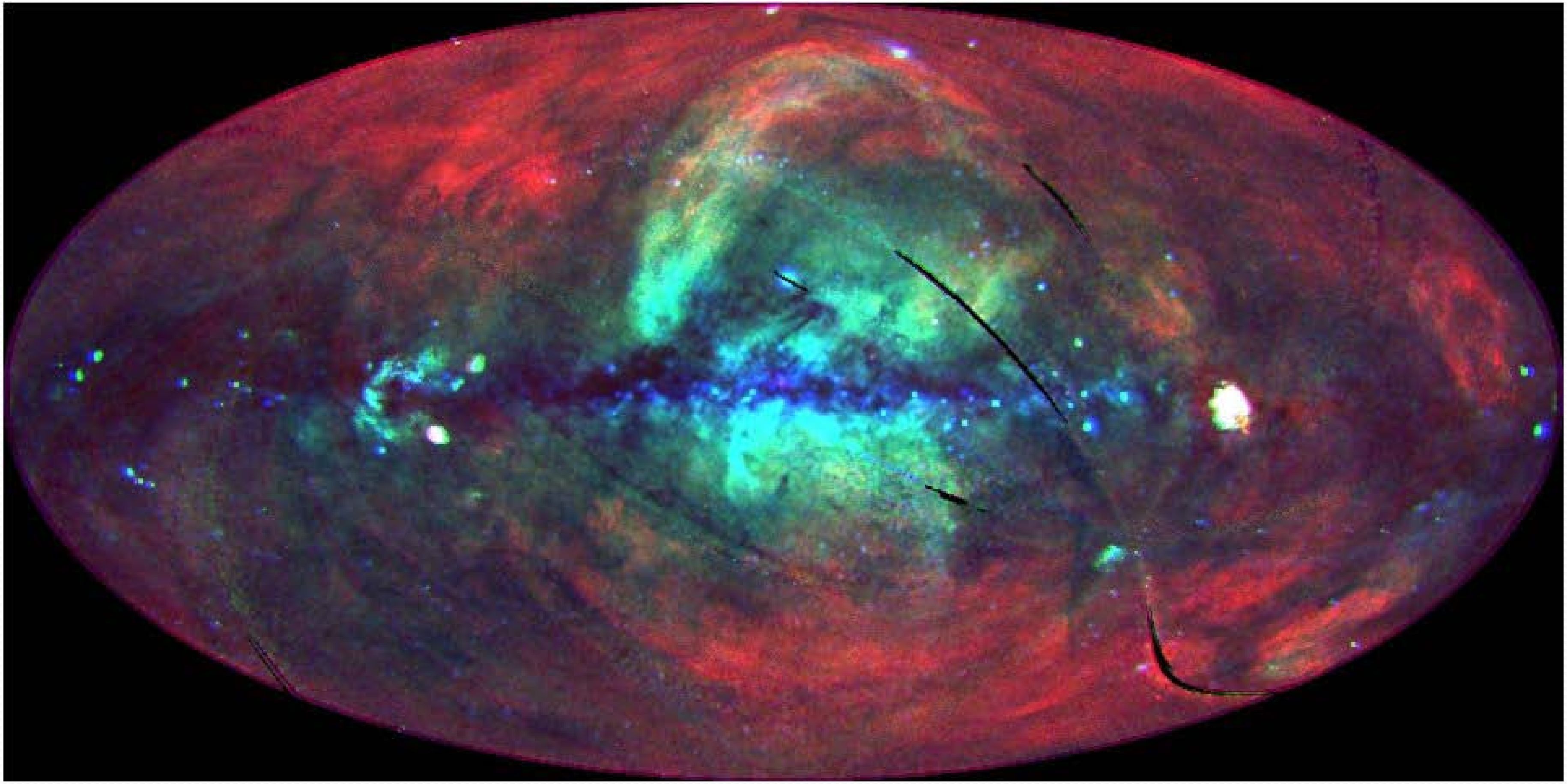
0.0004
0.0006
0.0008
0.001
0.0012
0.0014
0.0016
0.0018
0.002



RASS Red: 0.1-0.284 keV Green: 0.5-1.0 keV Blue: 1.0-2.0 keV

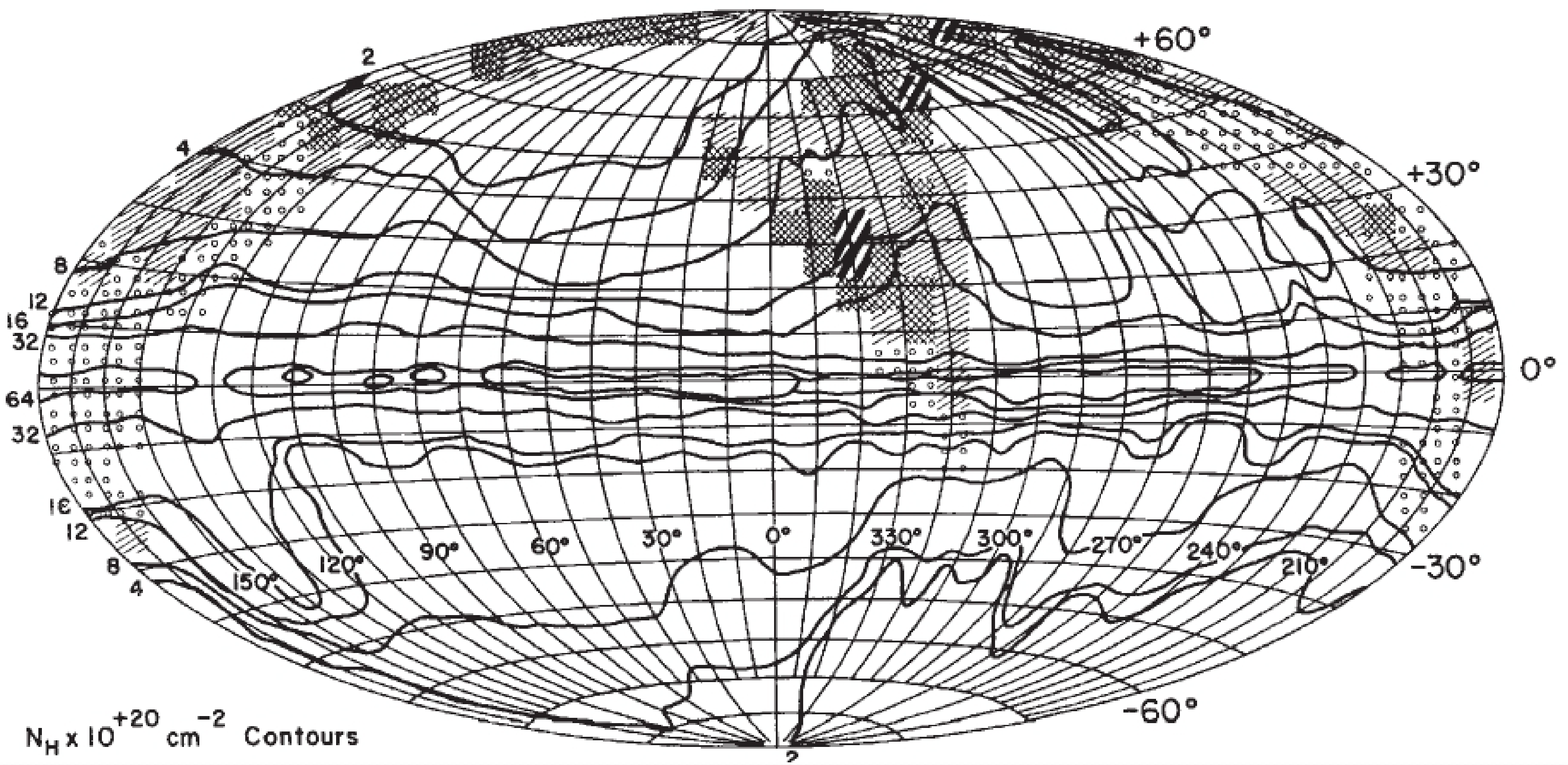
Galactic Diffuse X-ray Emission – Just What Do I Mean?

- Morphology
  - Emission extended on scales of 10's of degrees and greater
    - In general no SNRs or superbubbles
      - Unless they are very close (e.g., Loop I, Monogem, Eridanus)
      - Even then discussed more in terms of a background
  - Includes: Galactic Bulge, Local Hot Bubble, Galactic Halo, etc.
- Spatial Distribution
  - Observed distribution strongly modulated by Galactic absorption
    - *Structure varies strongly with direction*
- Spectral Distribution
  - Primarily observed in the 0.1-2.0 keV band
    - Observed spectra strongly affected by *Galactic absorption*
    - In general the emission is relatively weak

History Lesson – Data

- Age of Discovery – first observed using sounding rockets in late 1960's [1,2,3]
  - Limited coverage – data at high and low Galactic latitude
  - First thought to be mostly extragalactic in origin – what could produce X-rays locally?
    - Stronger signal out of than in the Galactic plane
    - Generally caused by the absorption of the extragalactic flux
      - Emission in excess of the absorbed EG flux in the plane attributed to Galactic emission – nuclear bulge [1], Galactic point sources [2], etc.
      - Clumped ISM and emission of solar or terrestrial origin [3]

History Lesson – Data



Bowyer, Field, & Mack[1] ¼ keV band sounding rocket data

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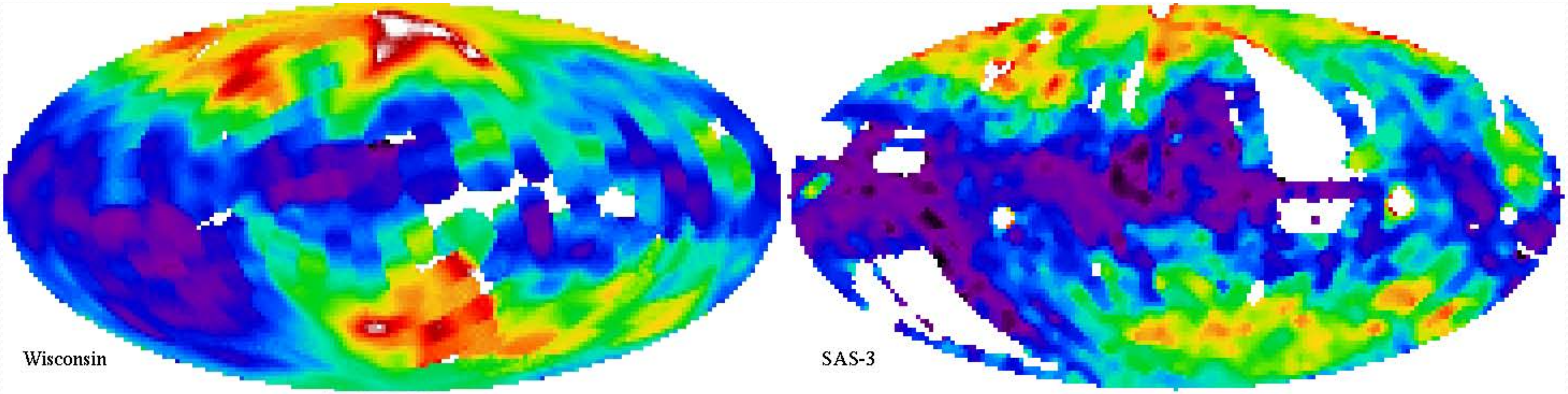
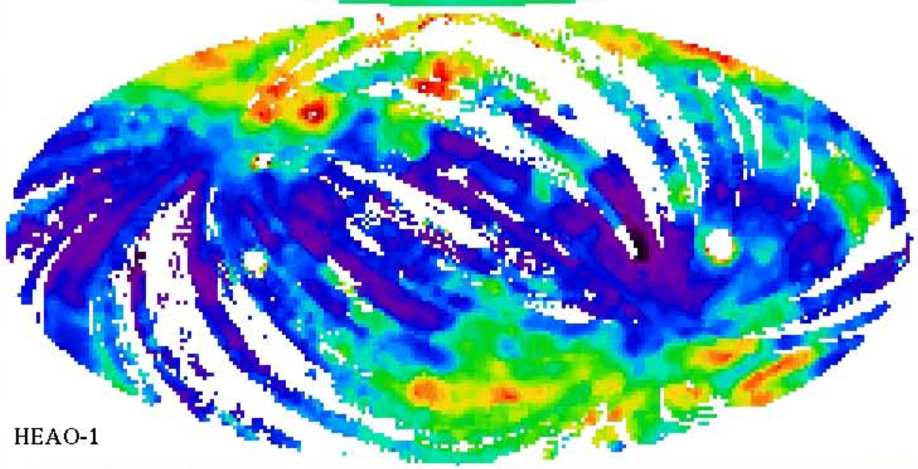
      - Clumped ISM and emission of solar or terrestrial origin [3]
- Age of Expansion – 1970's and early 1980's
  - All-sky surveys[4,5,6]
    - Spatial structure strongly linked to Galactic absorption – negative correlation with Galactic N_H
    - Structure varies strongly with direction

History Lesson – All-Sky Survey Data





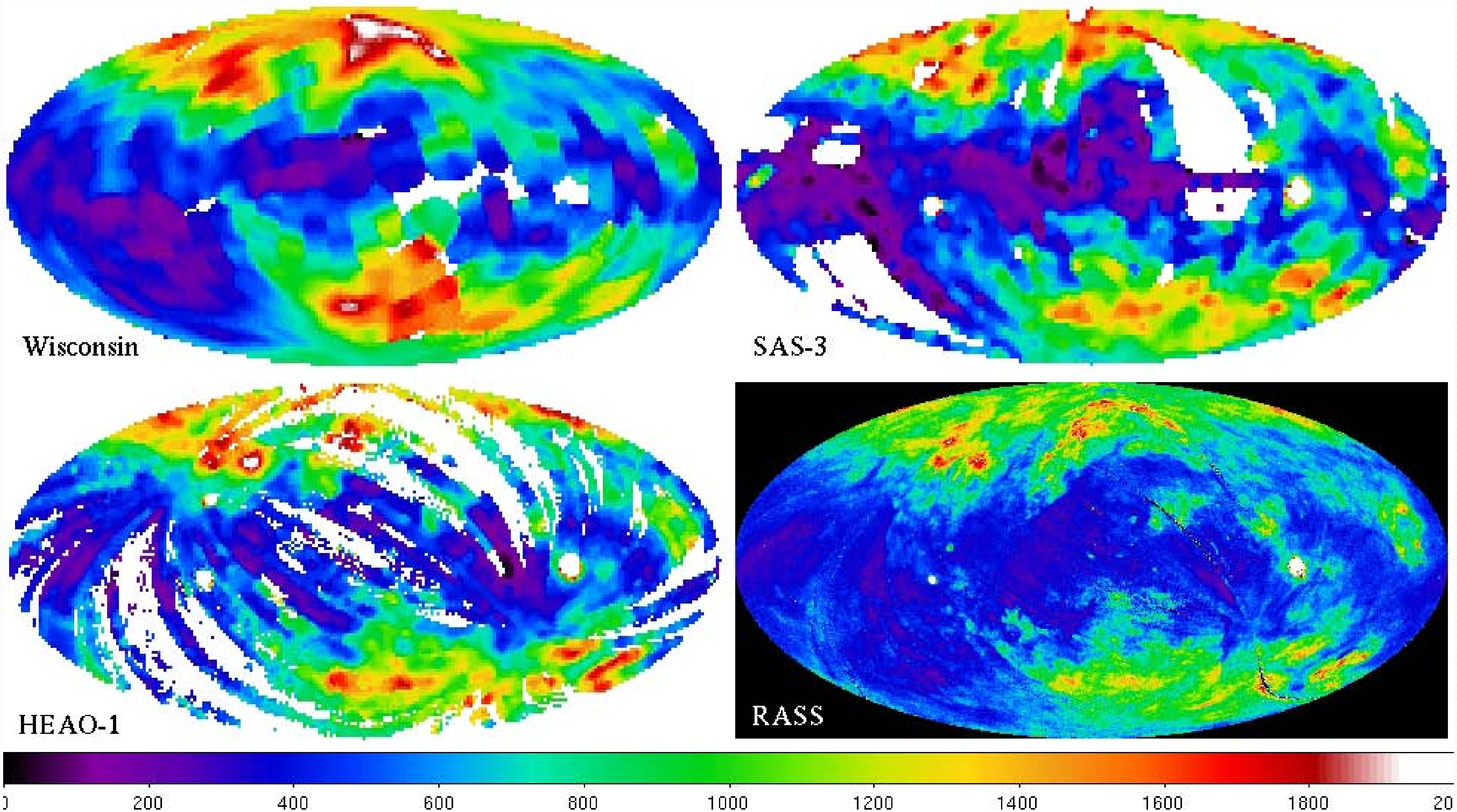
All-sky maps of the1/4 keV soft X-ray Background – The Wisconsin survey was comprised of 10 sounding rocket flights while SAS-3 and HEAO-1 were satellites.

Reasonably good agreement between maps.

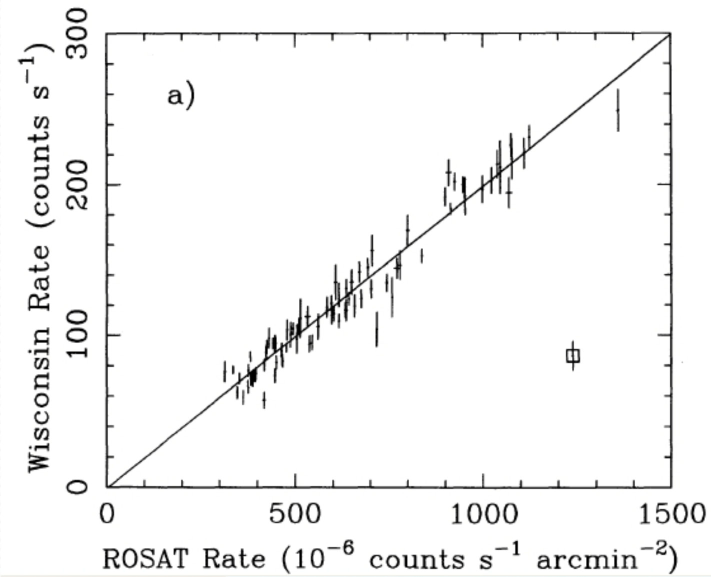
History Lesson – Data

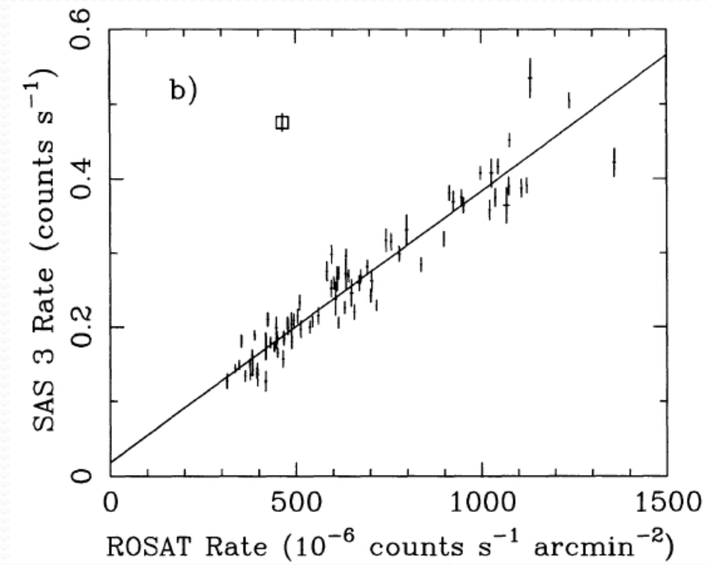
- Age of Refinement – 1990's
  - ROSAT All-Sky Survey [7]
    - Improved coverage by two orders of magnitude
    - Provided data which displayed a wealth of fine detail
      - Emission features – e.g., halo emission, SNRs [e.g., 8]
      - Absorption features – a.k.a., shadows [e.g., 9]
  - Blurred structure again agrees well with other surveys

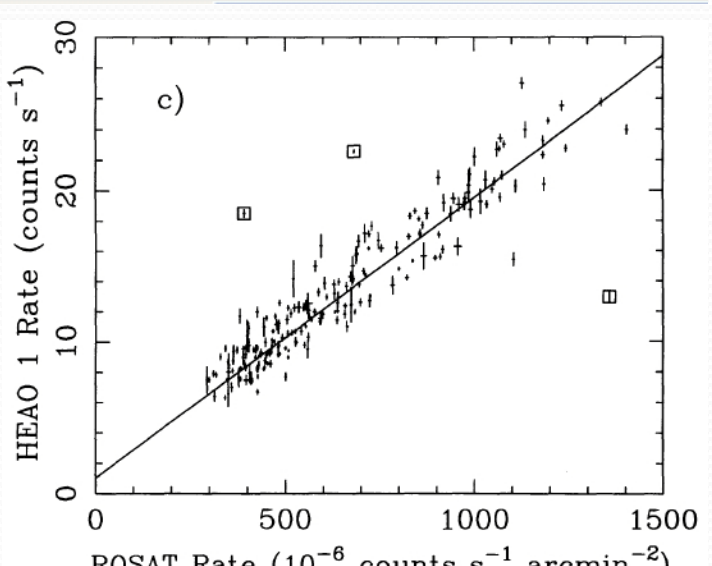
History Lesson – Data



History Lesson – Data



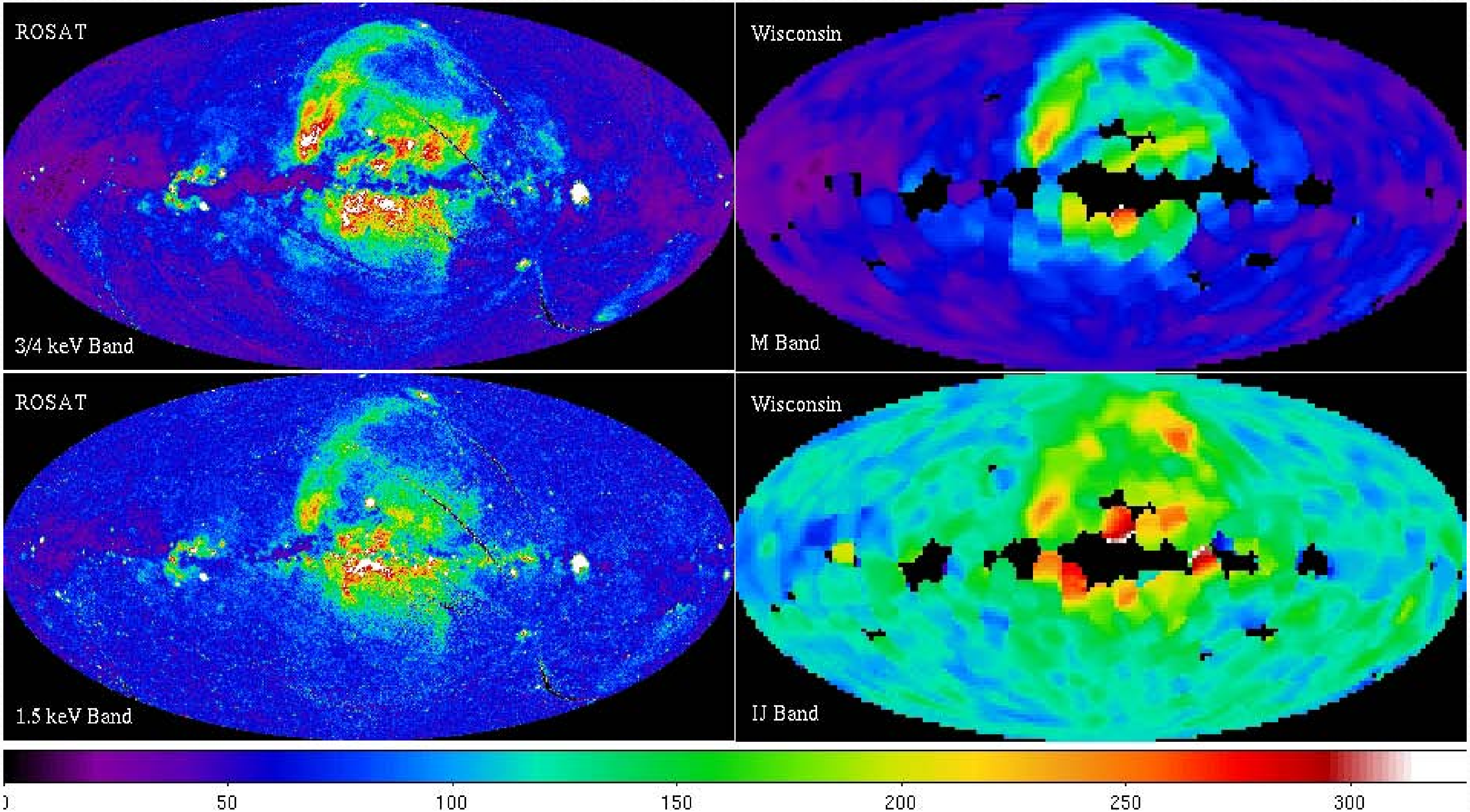




Offsets between both the SAS-3 and HEAO1-A2 and the RASS data likely indicate residual contamination in those two surveys.

Otherwise the four surveys are in very good agreement.

History Lesson – Data



History Lesson – Data

TABLE 5

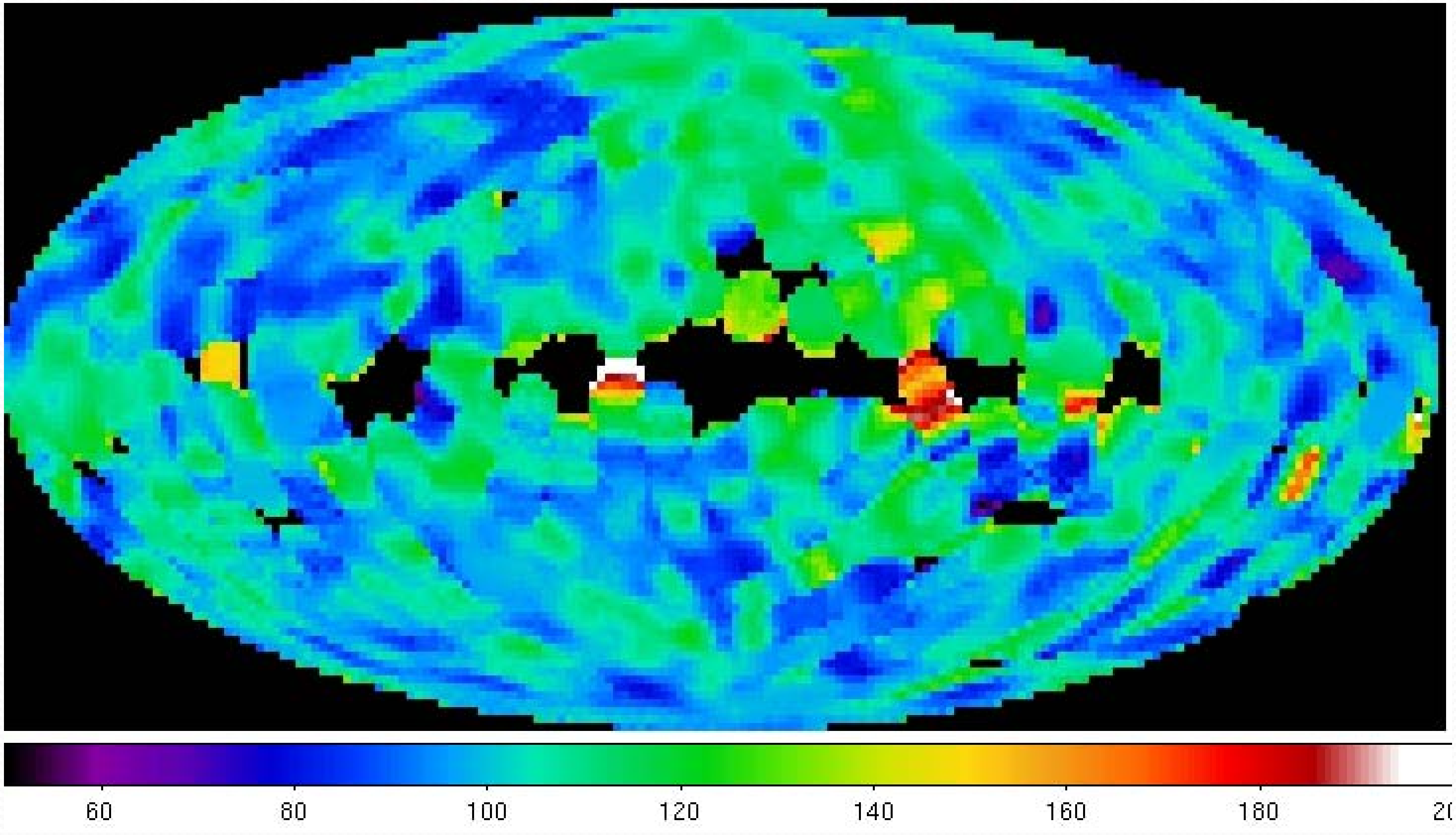
CORRELATION OF *ROSAT* DATA WITH PREVIOUS SURVEYS

Survey	Fitted Slope	Offset[a]	Predicted Slope	Difference[b] (%)
		$\frac{1}{4}$ keV Band		
Wisconsin/*ROSAT*	0.200 ± 0.005	-5 ± 15	0.186	+8
HEAO 1/ROSAT	0.0185 ± 0.0001	55 ± 8	0.0167	+11
SAS 3/ROSAT	$(3.65 \pm 0.07) \times 10^{-4}$	50 ± 11	3.38×10^{-4}	+8
		$\frac{3}{4}$ keV Band		
Wisconsin/*ROSAT*	0.390 ± 0.003	0	0.390	0
HEAO 1/ROSAT	0.0308 ± 0.0001	0	0.0299	+3
		1.5 keV Band		
Wisconsin/*ROSAT*	0.581 ± 0.003	0	0.544	+7
HEAO 1/ROSAT	0.0169 ± 0.0001	0	0.167	+1

[a] The *y*-intercept of the straight-line fit in Fig. 7 divided by the slope to express it in *ROSAT* count-rate units (10^{-6} counts s^{-1} $arcmin^{-2}$). This has been forced to be zero for the $\frac{3}{4}$ keV and 1.5 keV band fits.

[b] Percentage by which the fitted slope exceeds the value predicted using the published instrument-response functions.

History Lesson – Data



Wisconsin[4] 2-6 keV band

History Lesson – Data Summary

- Reasonably good agreement between the all-sky surveys
  - For the most part good to better than 10% in slopes
  - ¼ keV band offsets vary
    - Wisconsin/ROSAT spot on
      - ROSAT's multiple coverage aided cleaning
      - Wisconsin's better observation geometry reduced contamination
    - SAS-3 and HEAO-1 had significant offsets
      - ~10-20% of the cosmic background in low intensity regions
  - ¾ keV and 1.5 keV bands in good agreement
    - Poorer statistics (lower instrumental grasp and lower surface brightness)
- So, we have a good understanding of what the sky looks like
  - Data are relatively consistent over two decades of observation

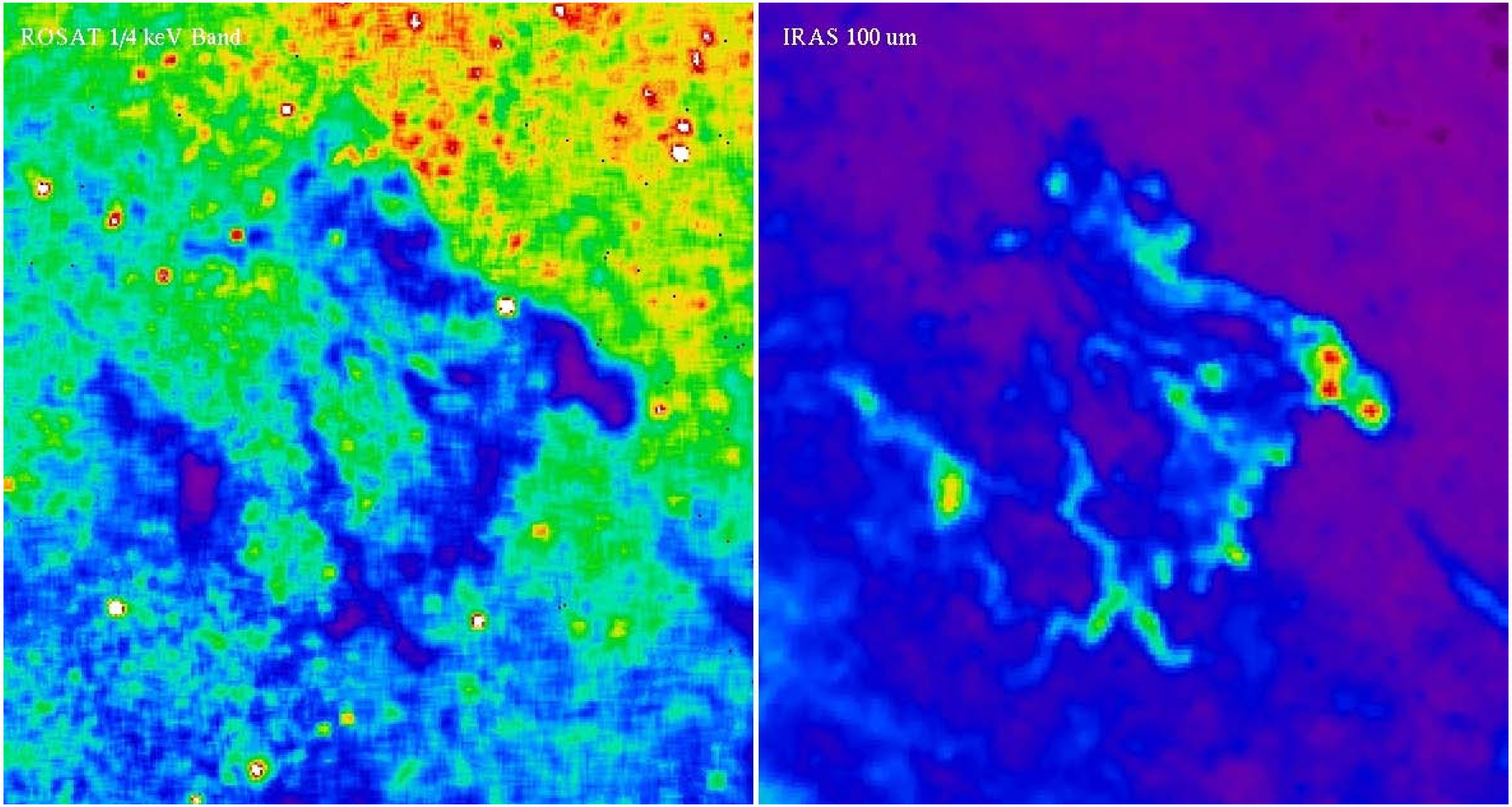
History Lesson – Models

- 1960's – Absorption Model
  - Extragalactic emission absorbed by Galactic ISM
    - ¼ keV band most strongly affected – τ=1 at $N_H \sim 10^{20}$ HI cm^{-2}
    - Non-zero flux in the Galactic plane from local sources (Milky Way, solar system, or non-cosmic backgrounds)
- 1970's – Modified Absorption Model[10]
  - Extragalactic and local emission
    - ¼ keV – Local emission with a hot plasma filling a cavity[11] in the ISM
      - Absorbed EG flux produced the observed structure, brighter out of the GP
    - 0.5-2.0 keV band – Absorbed EG flux with Galactic emission regions
      - SNRs, superbubbles, etc. – more emission observed in GP than expected
      - Population of discrete objects – M dwarfs?

History Lesson – Models

- 1980's – ¼ keV – Absorption, Interspersed, and Displacement Models – Enabled by lack of high-resolution data
  - Absorption model as in the 1970's
  - Interspersed model[12]
    - Highly clumped ISM with a matrix of hot plasma
    - McKee & Ostriker[13] view of the ISM, not supported by data[14,15]
  - Displacement Model[16]
    - Most observed emission originates with the Local Hot Bubble
      - Variation in observed flux due to different path lengths in the plasma
      - Residual emission from the EG power law
    - Not inconsistent with any observational data
      - Little variation in the observed ¼ keV band hardness ratio
      - LHB extent determined from X-rays agrees with extent of cavity
- 1980's – 0.5-2.0 keV – No Significant Change

History Lesson – Models



Shadowing by the Draco Nebula[17] – few hundred pc distant
=> Diffuse emission arising in the Galactic halo

History Lesson – Models

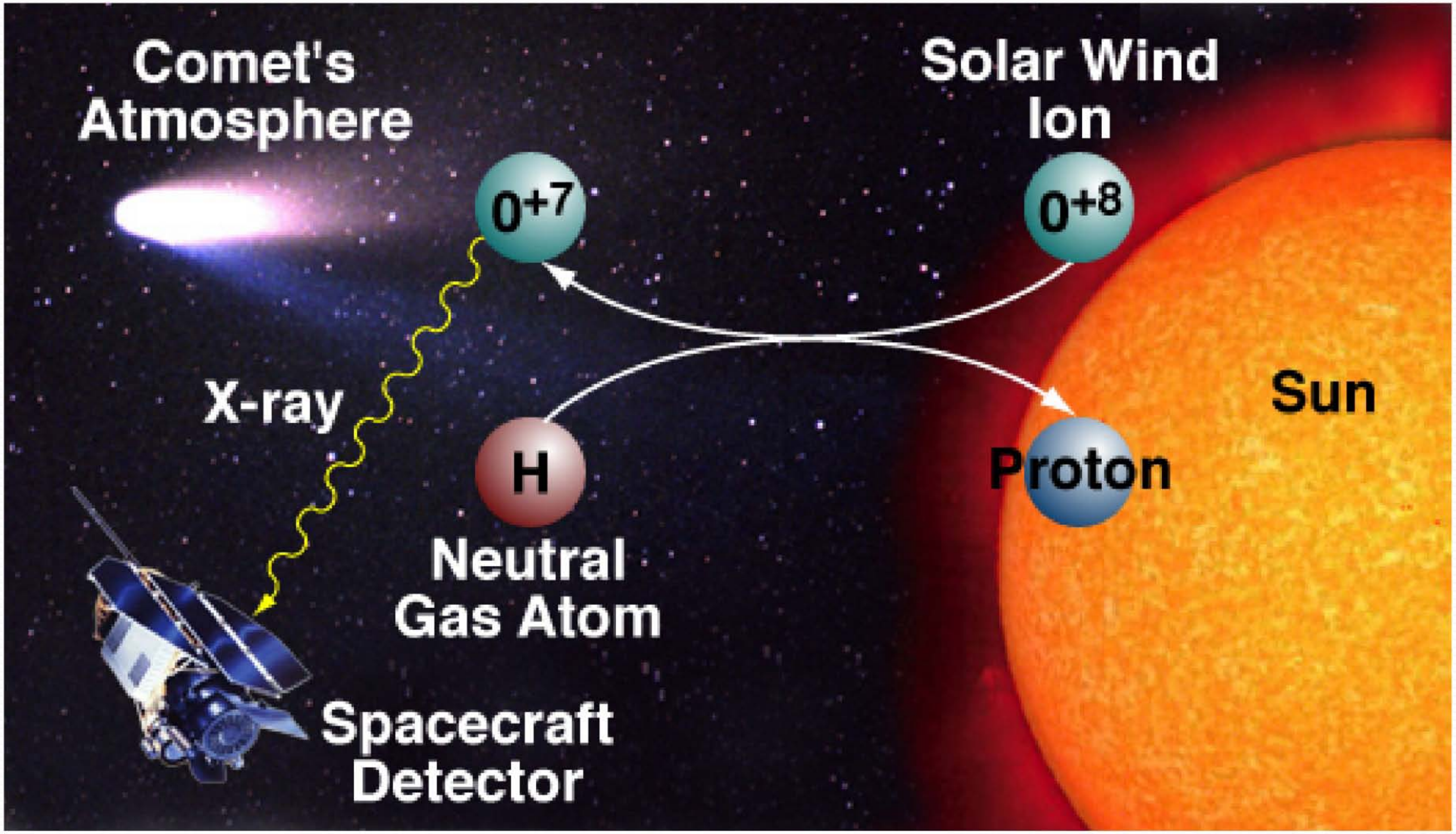
- 1990's – ¼ keV – Displacement Model with Halo Emission[18]
  - After 20 years of searching for shadows ROSAT provided them
  - Displacement model still produced most of the observed flux
    - Some regions of bright emission at low Z in the halo – e.g., Draco
    - Some sharing of the low nH regions with HII gas[19] – RBE (βCMa)
  - Absorption Model
    - Co-opted into the modified displacement model
  - Interspersed Model
    - Required ISM clumping ruled out

- 1990's – 0.5-2.0 keV band – No Significant Change

History Lesson – Models

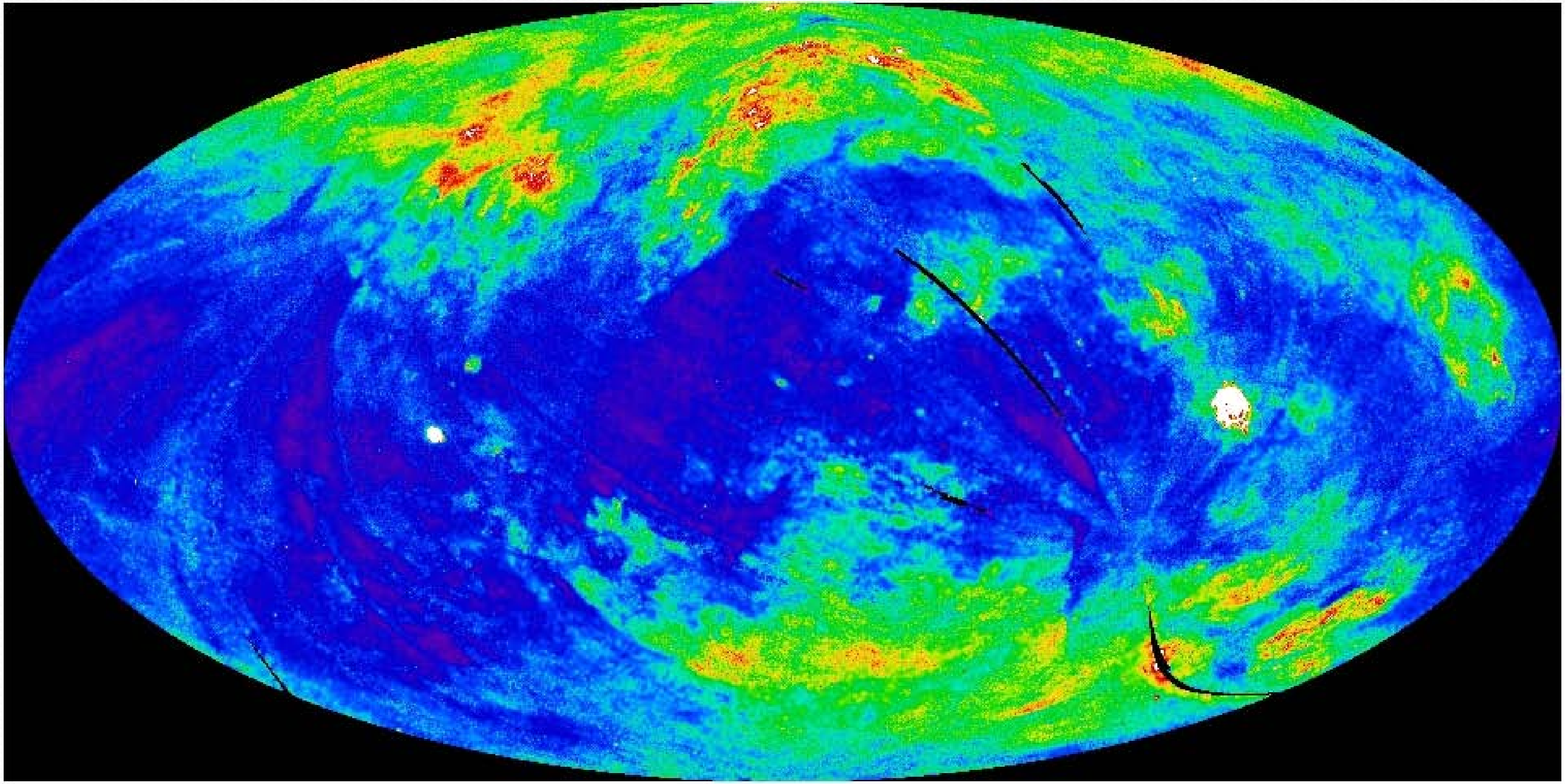
- 2000's – Almost Back to Square One
  - Enter solar wind charge exchange

Solar Wind Charge Exchange

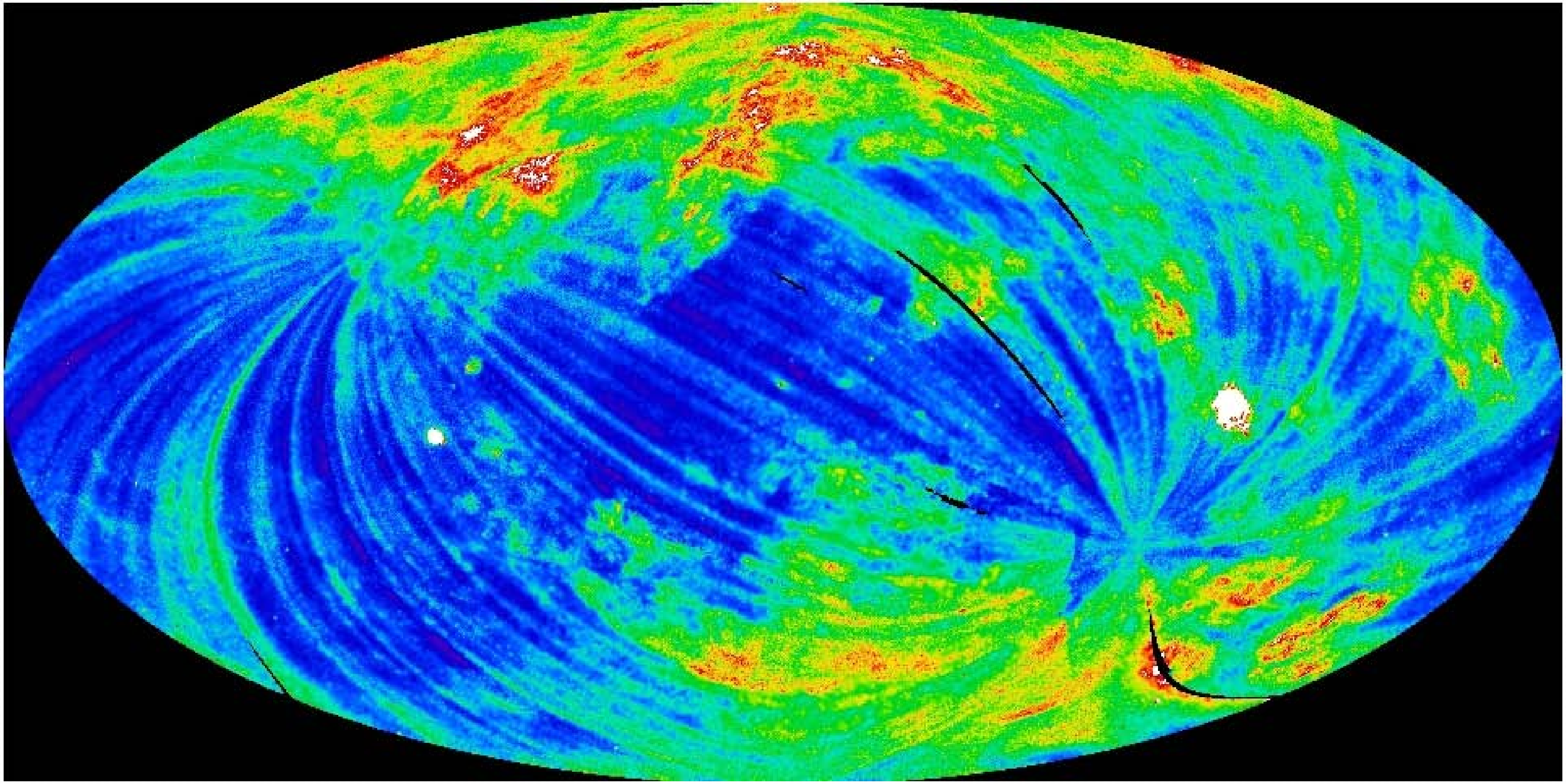


History Lesson – Models

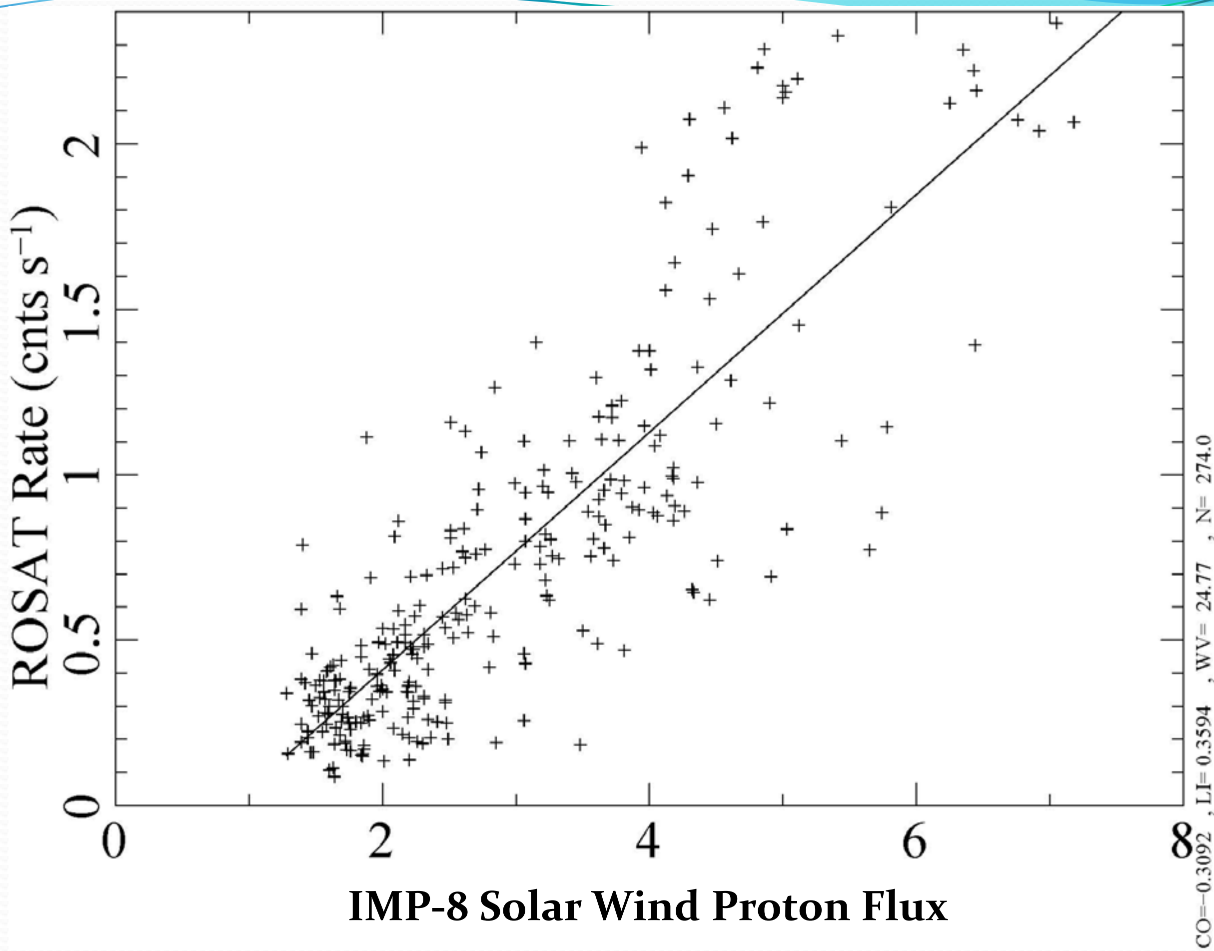
- 2000's – Almost Back to Square One
  - Enter solar wind charge exchange
    - First identified as comet X-ray emission mechanism[20]
    - Suggested as the source of contamination observed during the RASS[21]
    - Strong temporal variation from the SW interacting with Earth's exosphere[22]
    - Uncertain contribution from IS neutrals distributed through the heliosphere
      - ¼ keV Band – from 25-100% of the minimum surface brightness in the Galactic plane[23] – Back to the 1960's
      - ¾ keV Band – Nearly all observed foreground emission[24]



RASS ¼ keV band image with temporal filtering and all backgrounds subtracted
Aitoff-Hammer projection in Galactic coordinates centered on the Galactic Center.
Blue is dim while red is bright (Snowden et al. 1997).



RASS ¼ keV band image without temporal filtering but with the particle background and scattered solar X-ray background subtracted. The striping is due to SWCX, a.k.a. long-term enhancements.



Correlation between the IMP-8 solar wind proton flux (units of 10^8 cm^{-2} s^{-1}) and the ROSAT LTE count rate at the north ecliptic pole (units of counts s-1), with a best-fit linear curve. Extrapolating to zero => an offset of ~15-20% of the minimum ¼ keV surface brightness.

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  - Modified displacement model still produces most of the observed ¼ keV flux

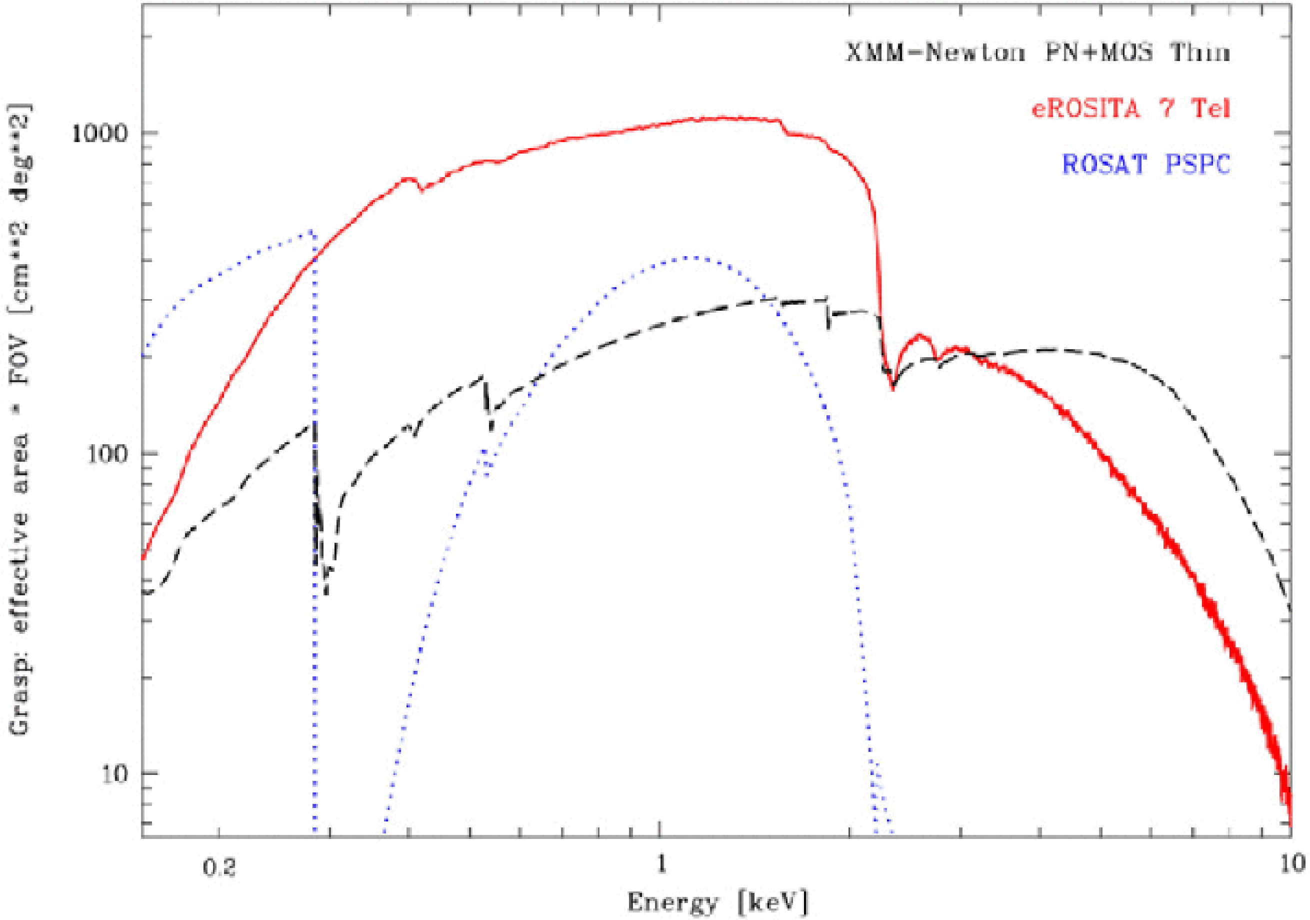
Milky Way SXRB Emission Mechanisms

- Thermal Emission (not necessarily in thermal equilibrium, not necessarily with solar abundances)
  - Supernova remnants – some old and large and relatively cool, e.g., LHB, Monogem[25]
  - SNRs, Stellar wind bubbles/superbubbles – some old but not quite so cool, e.g., Loop I, Eridanus Enhancement[26]
  - Galactic Bulge[7] – Scale height of ~1.9 kpc, T~$10^{6.6}$ K
  - Galactic Ridge – Two components mapped by Fe lines at 6.7 and 7.0 keV[27], scale height ~0.25 kpc
- Charge Exchange – Not just for the solar system and magnetosheath – Edges of SNRs and Superbubbles

Milky Way SXRB Emission Mechanisms

- Like most of X-ray astrophysics – thermal emission implies an energetic origin, e.g., SNe, stellar winds of clusters of young stars.
  - Even if the plasma is no longer hot[28] (delayed recombination)
- The existence of a halo around the Milky Way is an open question
- Origin of diffuse emission in the lower halo still an open question – *in situ* SNe, Galactic fountains, etc.
  - Probably a mixture of sources which need to be analyzed on a case-by-case basis
  - Have to see them first

eROSITA – Best/Only Thing Since ROSAT



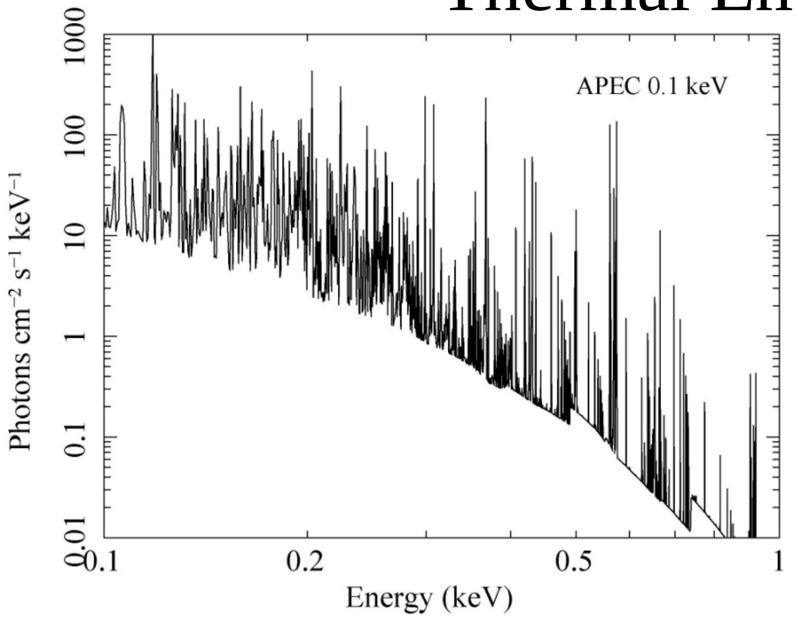
eROSITA's grasp far exceeds that of the ROSAT PSPC for E>0.284 keV, ~5x at 0.6 keV.

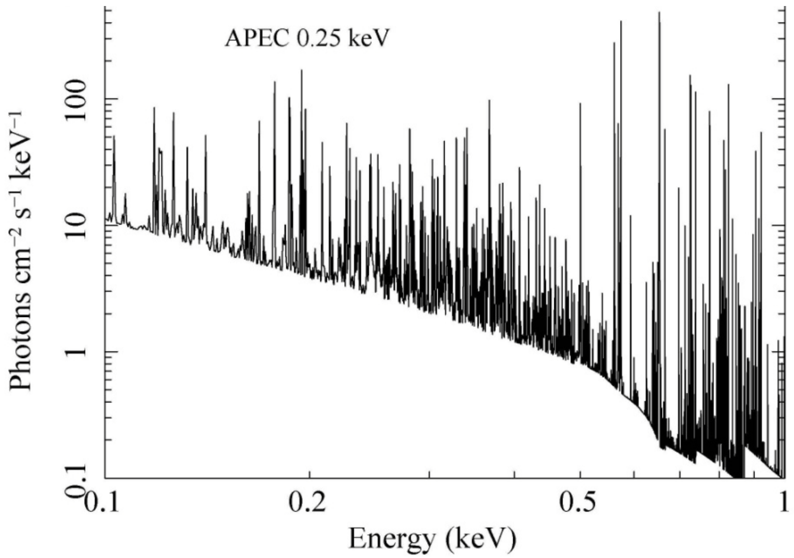
The mean eROSITA survey exposure of 2000-3000 s exceeds the RASS by a factor of ~5

At 0.6 keV (the energy of the OVII and OVIII lines) the detected count density will be a factor or ~25x higher

⇒~1-5 counts arcmin^{-2} in the ¾ keV band

Thermal Emission Spectra

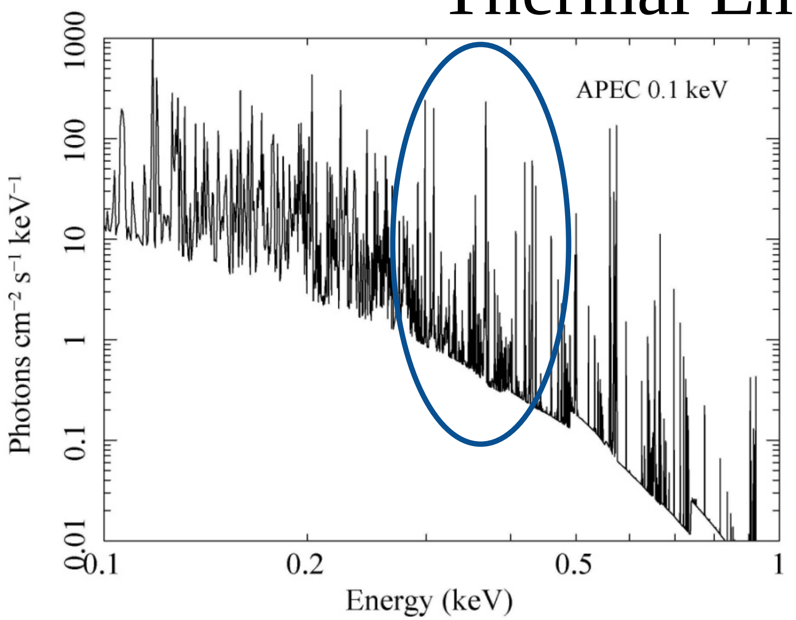


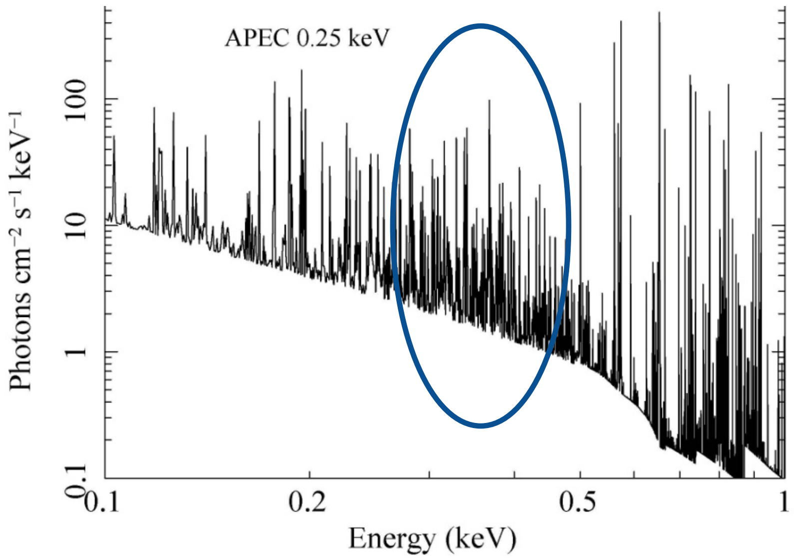


Sensitivity to lower energy X-rays vital to understanding the diffuse X-ray background

Carbon gap (0.284-0.45 keV) untouched territory for all-sky surveys – there should be considerable emission from the C and N emission lines

Thermal Emission Spectra





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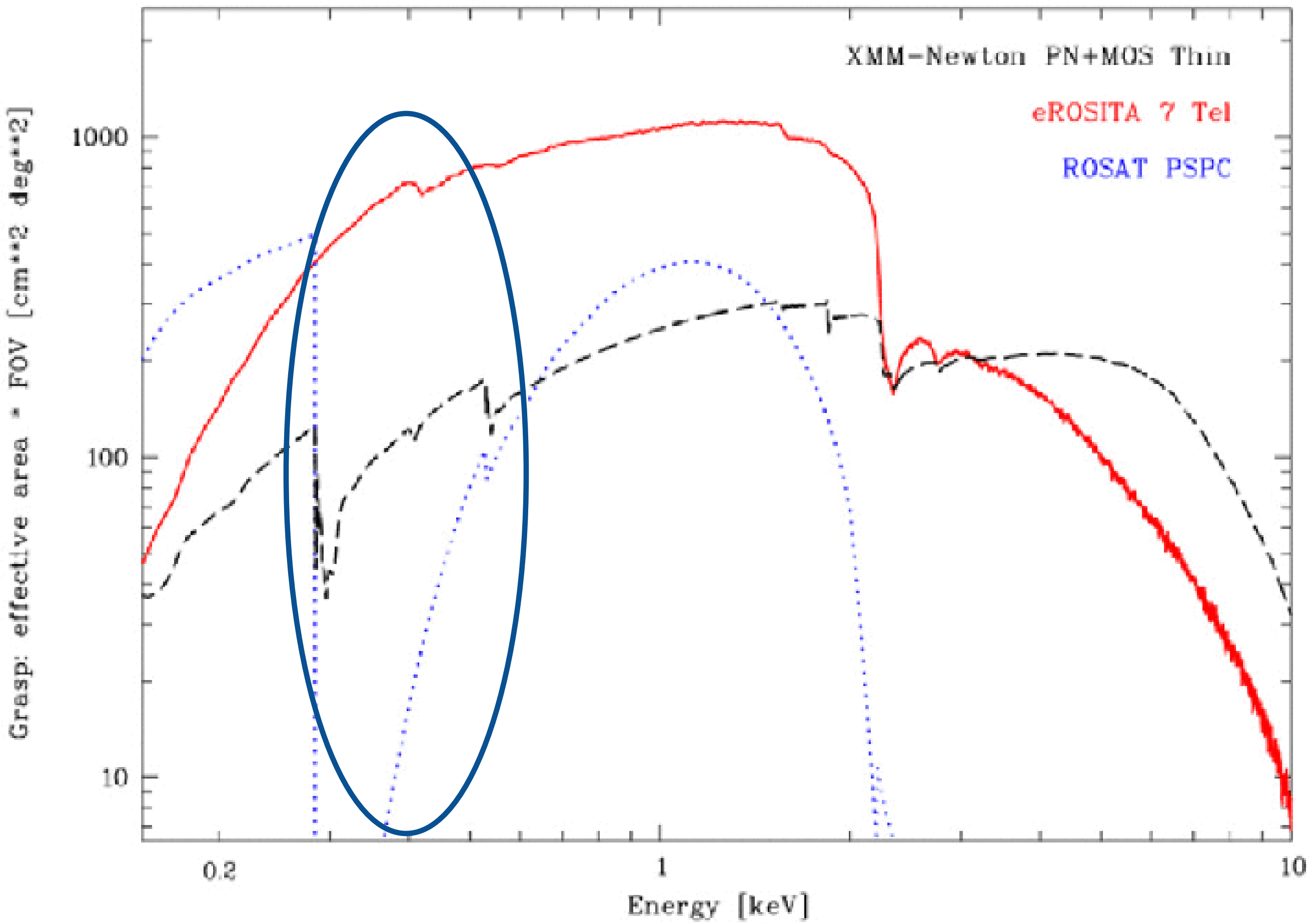
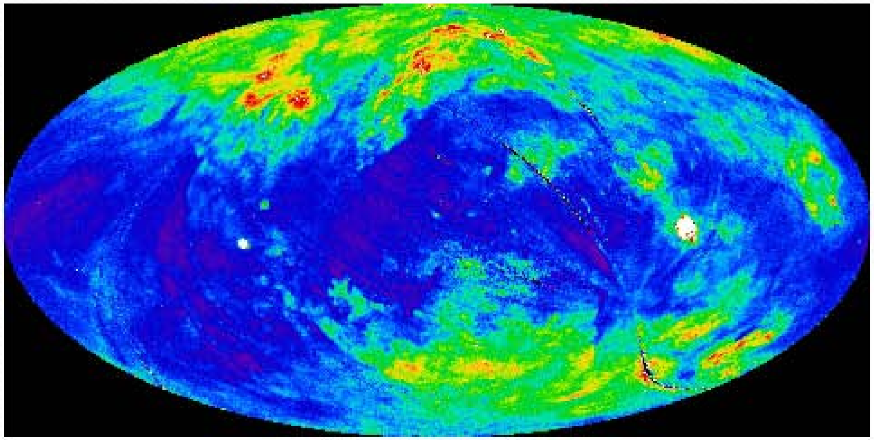
eROSITA

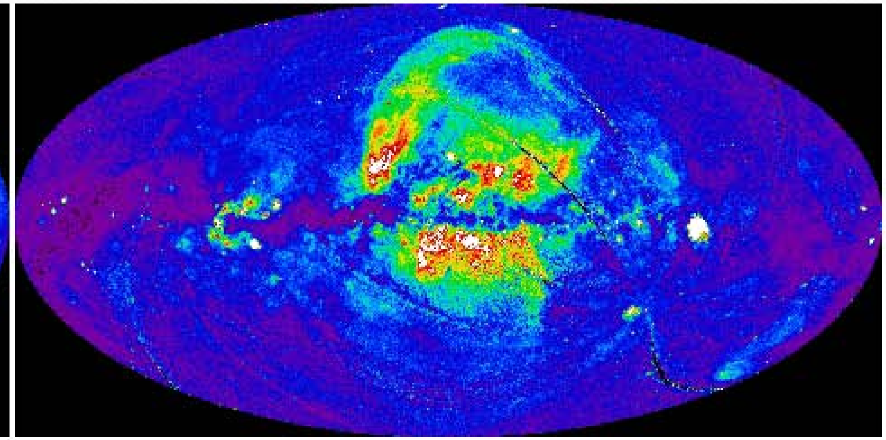


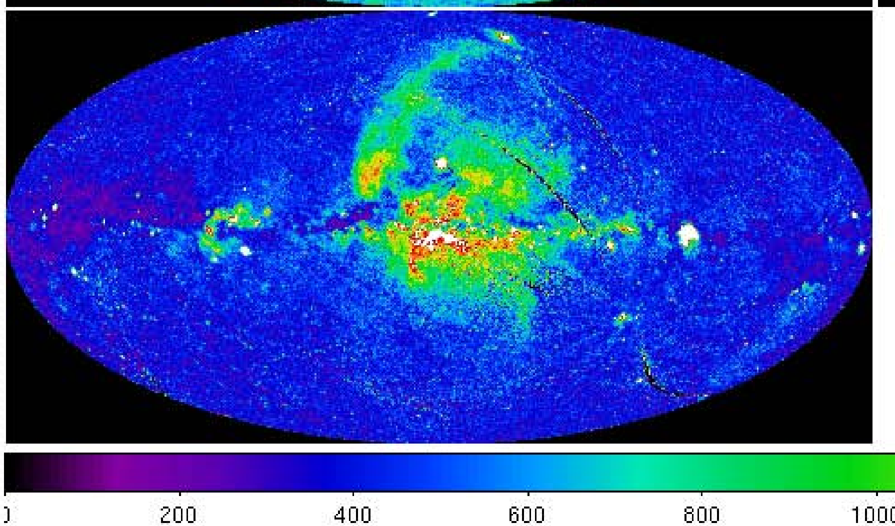
eROSITA's grasp in the carbon gap is unique and will allow the investigation of a spectral and spatial regime never before observed.

IS absorption cross sections go as ~E^{-3}, meaning that 10^6 K emission regions such as the LHB and Draco will be observable through ~5x the column density of HI

eROSITA Benefits







Better Statistics
- Multiple coverage at different epochs

Better Background Removal
- Better sampling of heliospheric SWCX
- Reduced magnetospheric SWCX

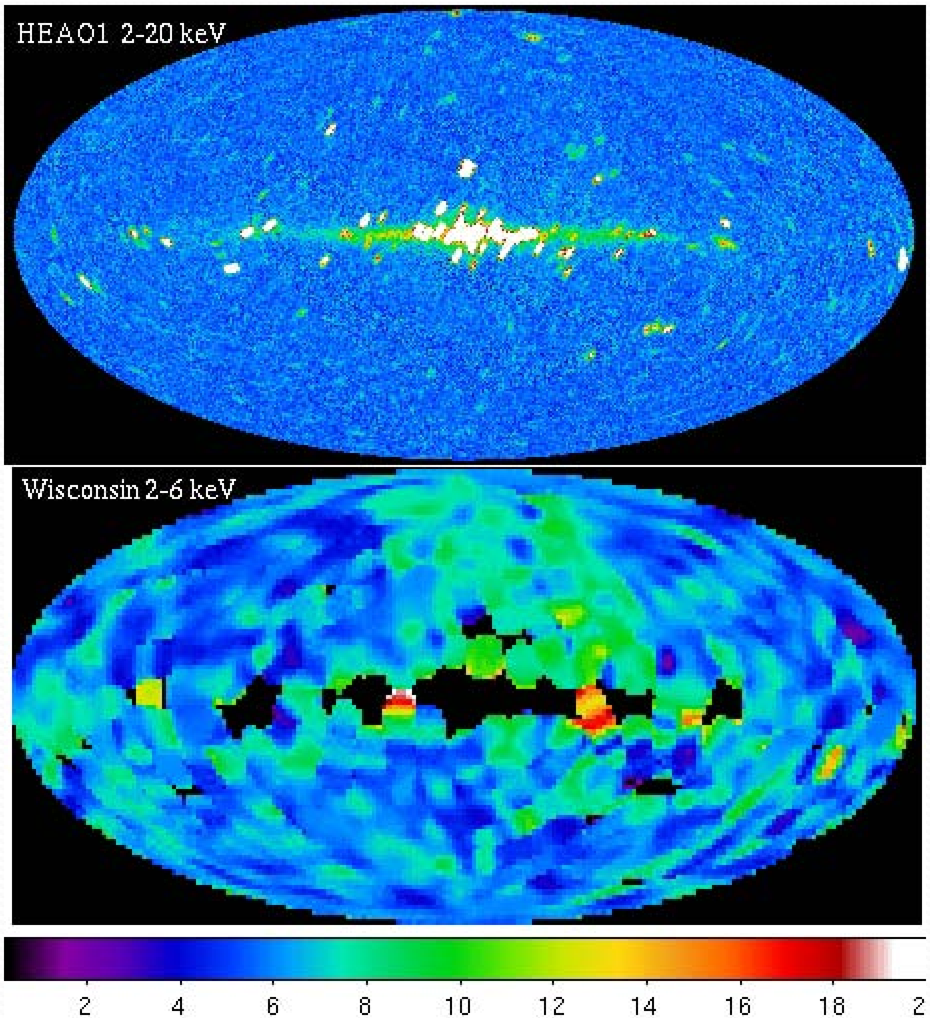
Better Energy Resolution, Average PSF

First all-sky survey in the 2-10 keV band in decades – with vastly improved statistics!

First all-sky survey in the 0.284-0.45 keV band

Magnetosheath SWCX vastly reduced

eROSITA Benefits



Hard X-ray survey – includes both unresolved cosmological sources with a cosmic variance and diffuse emission mostly associated with the Galactic plane and center.

What will the eROSITA diffuse X-ray sky look like in the 2-8 keV band?

Better angular resolution to remove point sources (or even study them)

Better grasp and exposure to provide for better statistics

Non-cosmic (particle) background may be more problematic.

References

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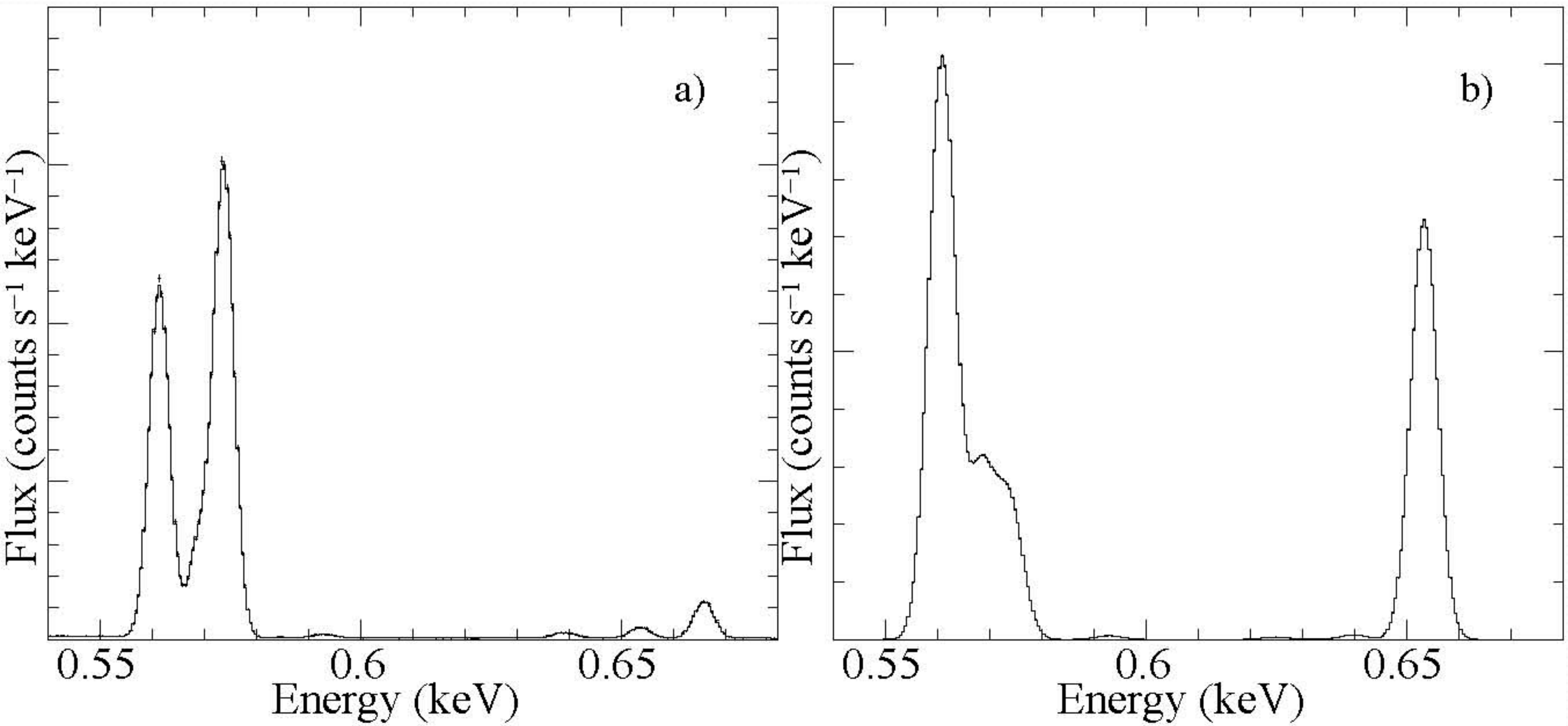
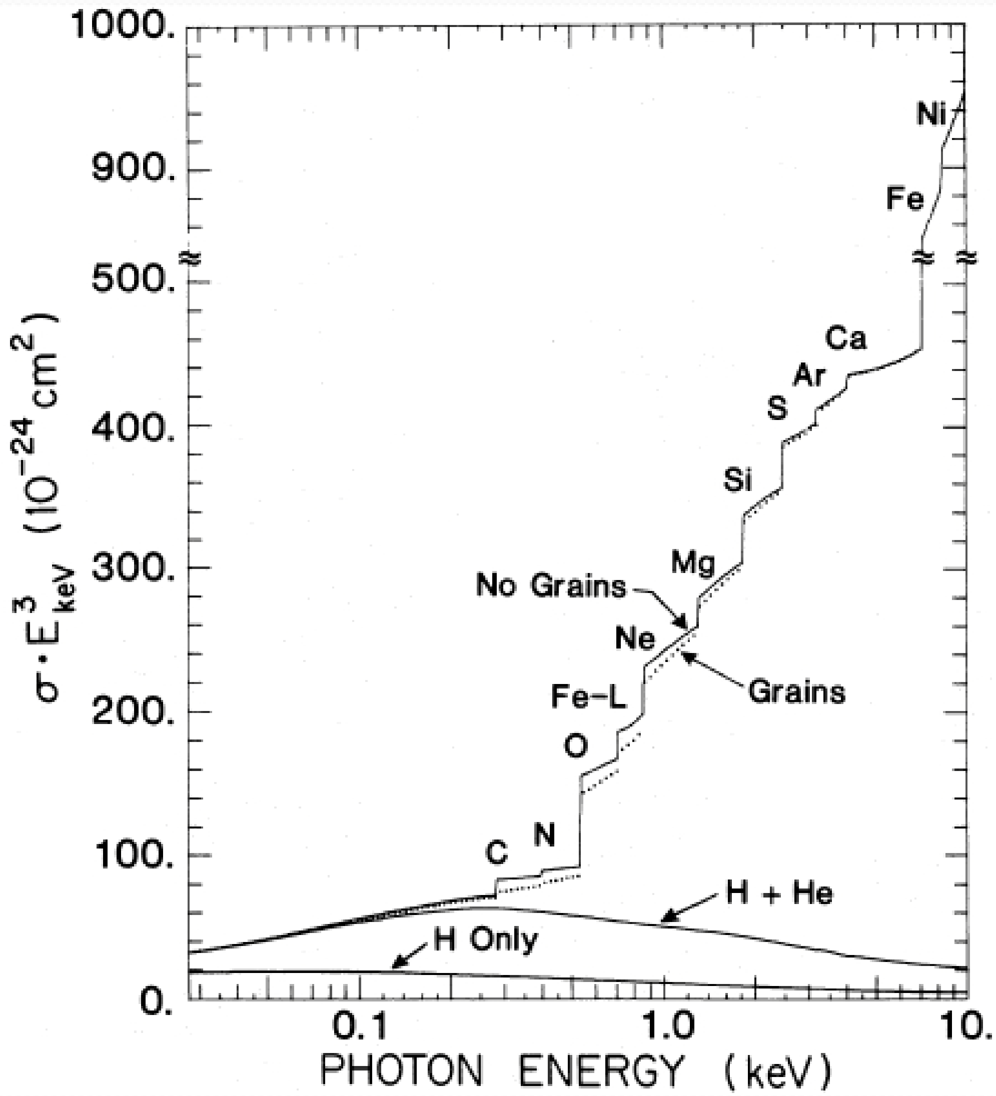
CX and Thermal Emission Spectra



Model spectra of the O VII and O VIII lines for (a) thermal (equilibrium) and (b) SWCX spectra

Same lines, different power distributions – spectral shift can provide a mechanism to distinguish between emission origins

eROSITA



ISM absorption goes as $\sim E^{-3}$ with jumps due to element absorption edges

The unit cross section for X-rays at 0.4 keV is ~1/6 of the cross section at 0.2 keV[27]

With emission from the C and N lines Galactic regions of 0.1 keV plasmas, similar to those in the LHD and lower Galactic halo in the direction of Draco, will be easier to observe

eROSITA will provide a new and unique view of the local Galaxy!!!