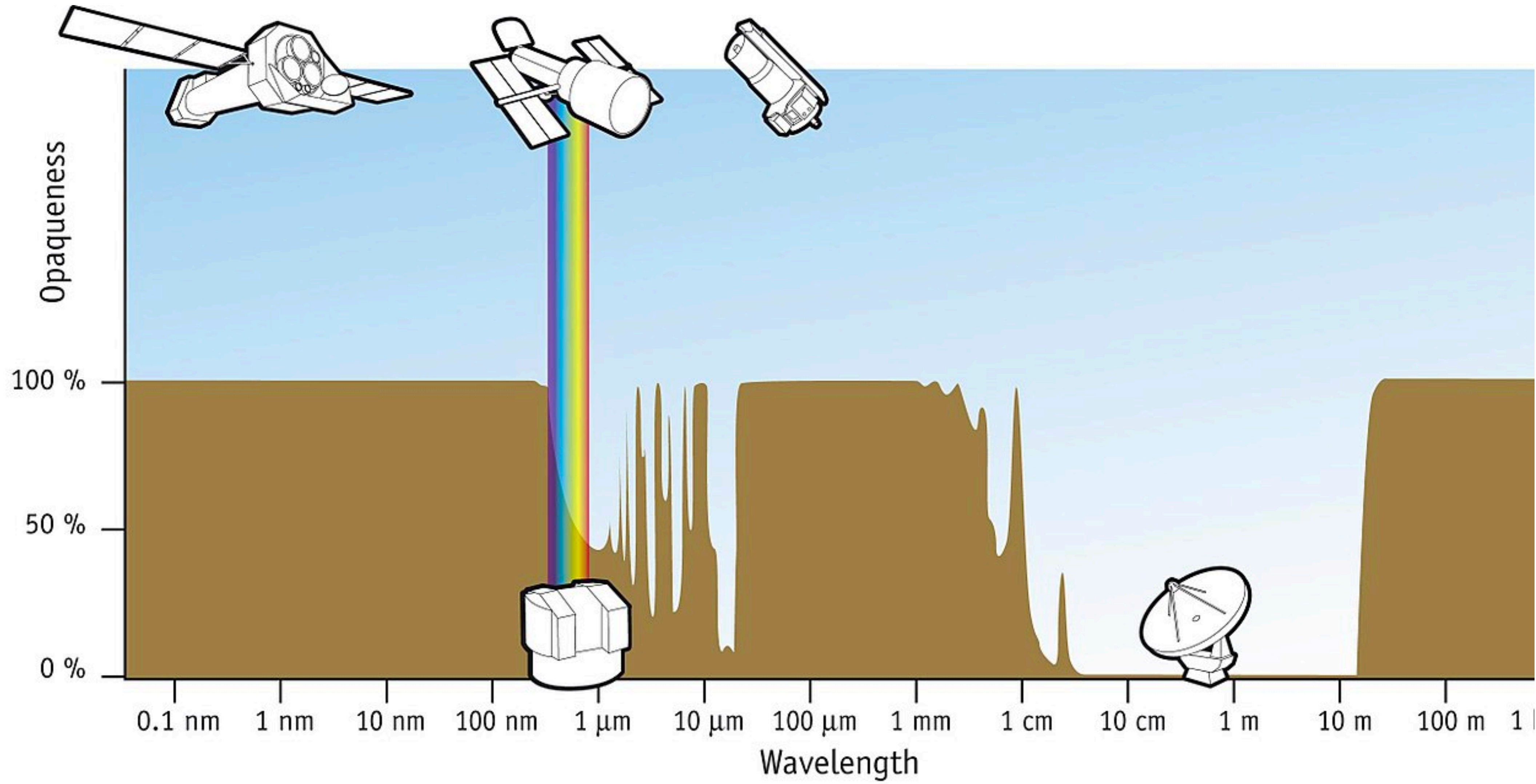
X-rays from the Sky

Scientists and Friends, Wind Crest

Dick Edgar, 13 May 2020 web: RichardJEdgar@github.io

- “Tell me one thing that you discovered yourself,” said Dean Seidel over dinner last fall sometime.
- This talk is a retelling of what I said then.
- The short answer is that I collaborated a lot… Never mind. Stuff I did with my friends counts.
- Short answer: I disproved my own thesis.
- I’m an x-ray astronomer. I did a PhD in Physics at the University of Wisconsin in Madison, in a “Space Physics” group that studied the diffuse soft x-ray background… What’s that?
- To back up a little further, why x-rays? And why from space?



Opaqueness
100 %
50 %
0 %
0.1 nm
1 nm
10 nm
100 nm
1 µm
10 µm
100 µm
1 mm
1 cm
10 cm
1 m
10 m
100 m
Wavelength

Electromagnetic Radiation

- Nearly all of what we know about the universe beyond the Earth comes from analyzing electromagnetic radiation. Stuff happens out there; when charged particles (electrons, protons, ions…) are accelerated, they radiate waves in the electric and magnetic fields that can propagate vast distances.
- Some wavelengths (optical, radio) come to us on the ground. The rest, after traveling hundreds to billions of light years, get absorbed in the atmosphere in the last 10 km or so. (This is a good thing, for those of us living here on the ground.)
- To see x-rays (or ultraviolet, or big chunks of the infrared) at all, you need a detector in space.

Our Galaxy

- A Galaxy like ours consists of a bunch of different kinds of stuff:
  - ★ Dark matter… we know about this only because of its gravity. It's a flattened ball (oblate spheroid, maybe twice as wide as it is high).
  - ★ Stars. About 90% of the ordinary matter (made of protons, neutrons and electrons) is in stars. Our Sun is a star. Stars form a thin disk.
  - ★ Gas. The other 10% of the ordinary matter is the "Interstellar Medium," gas out between the stars. There's about one atom per cubic centimeter on average, but that's a bit deceptive.

The Interstellar Medium

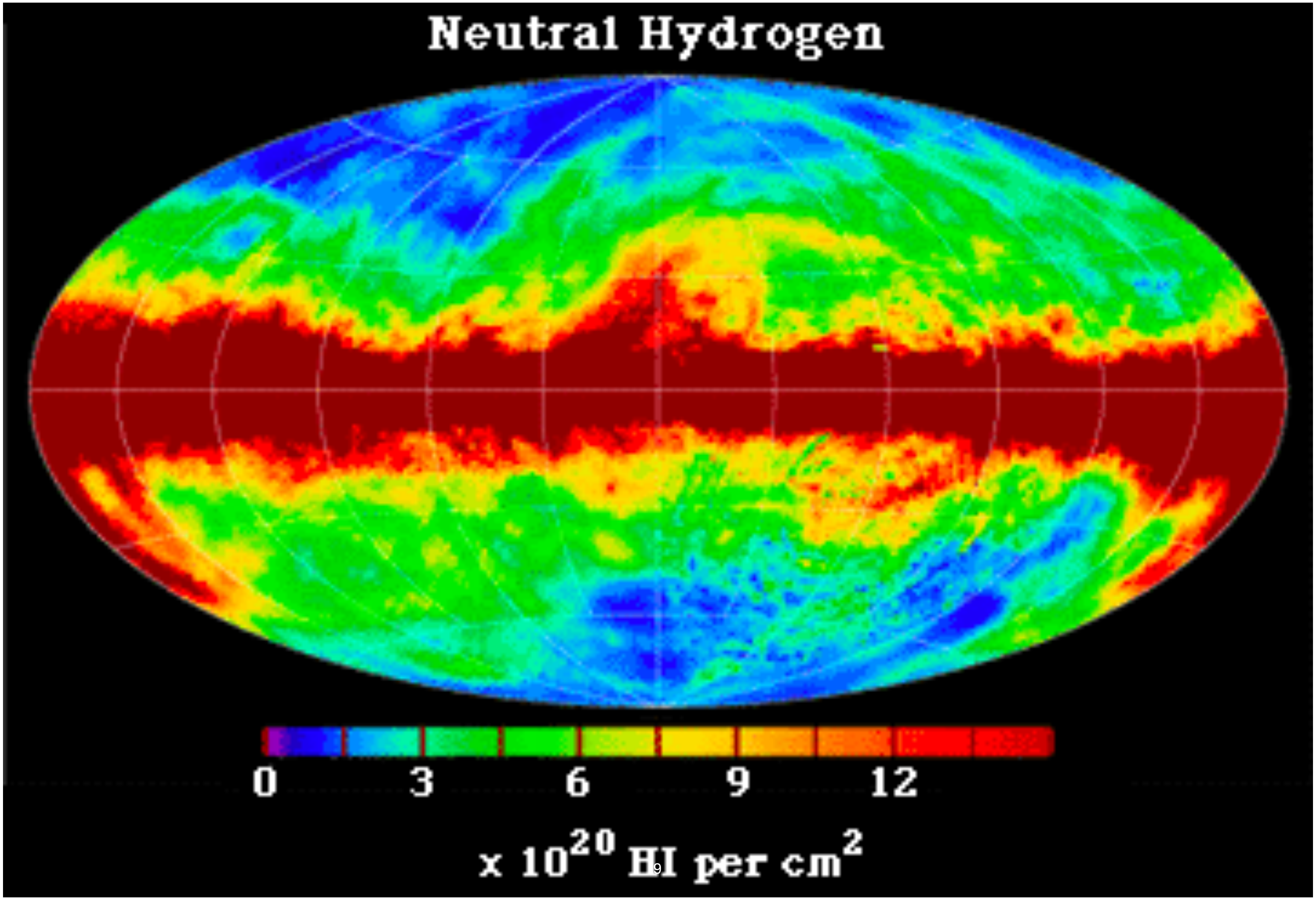
- Some of the ISM is in cold, opaque "Molecular Clouds," which we observe in CO and other molecules. Mostly H_2 and dust; temp about 10 K, densities of 10^5 atoms / cm^3.
- Diffuse clouds, temp about 100 K, densities of a few atoms / cm^3. There's a fair amount of dust here, also.
- Warm gas, temp about 10,000 K, partially ionized, density 0.1 atoms / cm^3. There's some dust.
- Hot gas, temp about a million K, fully ionized, density .01 atoms / cm^3.
- "Dust" consists of silicates (Mg, Fe, etc.) and carbon (polycyclic aromatic hydrocarbons, PAH == little chips of graphite with H atoms around the edges).

Now back to x-rays

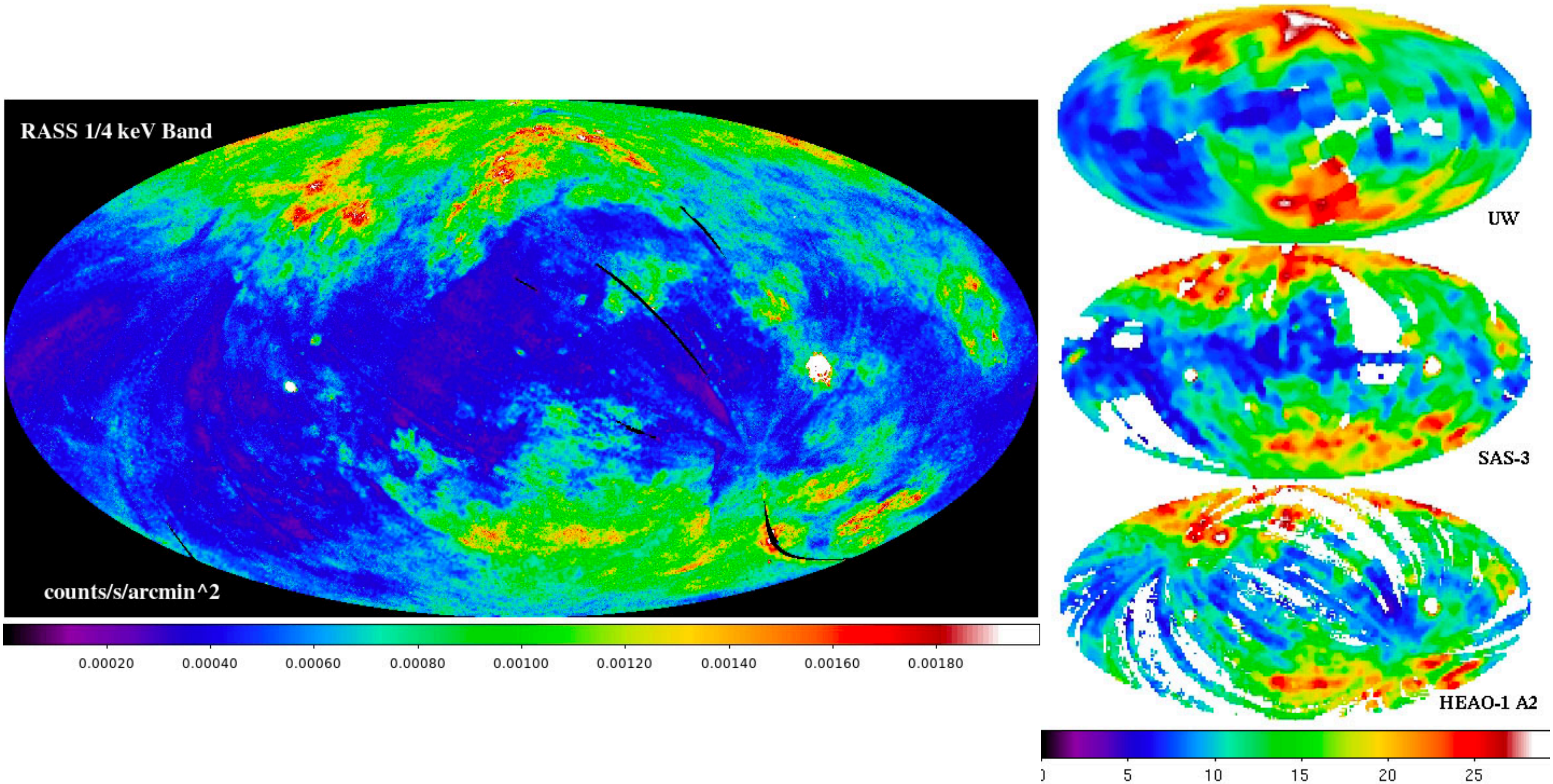
- If you look at the sky in x-rays, you see bunches of sources: stars, quasars, blast waves from old supernova explosions, clusters of galaxies, and so on.
- The ones that are bright in x-rays may or may not be the same ones visible in the optical or other wavelengths. In particular, x-rays penetrate the ISM better, so you can see things going on behind dark clouds (e.g. the center of our Galaxy).
- There's also a diffuse glow that covers the sky; the sky isn't nearly as dark in x-rays between identifiable sources as it is in the optical. This glow is the "Diffuse x-ray background"
- It's been known since the 70s that at high x-ray energies, it comes from cosmological distances; it's an assemblage of huge numbers of quasars.

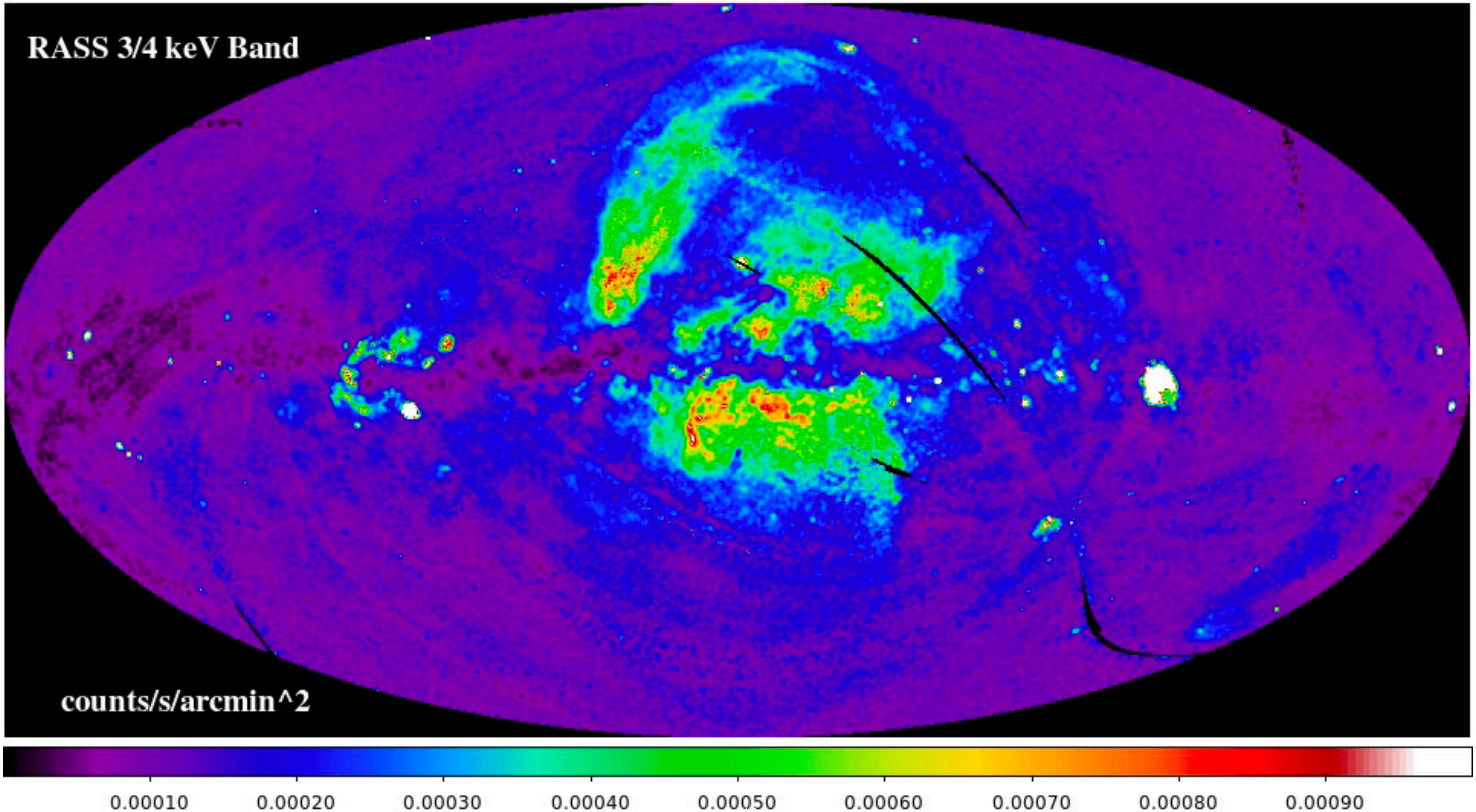
The Soft X-ray Diffuse Background

- X-rays interact with matter depending on their energy (i.e. wavelength). Lower energy x-rays interact much more strongly than higher energy ones.
- Bill Kraushaar had the idea of using this fact to essentially x-ray the interstellar medium of our Galaxy, by observing x-rays from the diffuse background at a range of energies, and watching the absorption happen as you look through more of the Galaxy.
- Since x-rays interact typically with inner-shell electrons in atoms, they hardly care at all about chemical bonds. You could make an inventory of everything out there, in either gas or dust.
- Here is a map of the sky in hydrogen atoms, made in the radio observing the 21 cm wavelength spin-flip line.


Neutral Hydrogen
0
3
6
9
12
x 10^20 HI per cm^2

- This is a map of the whole sky, in an Aitoff projection, which features equal area pixels. It’s in Galactic coordinates, so the Milky Way disk is seen edge-on across the middle (equator), and you can see there’s a lot more stuff between us and infinity at low latitudes than at higher latitudes.
- The Wisconsin group (Kraushaar et al) ran a program of sounding rocket flights using proportional counters with honeycomb-style collimators (no focusing optics) to map the sky in a series of about 20 rocket flights.
- Similar maps were made by the SAS-3 satellite (MIT) and an experiment on the HEAO-1 satellite (Penn State). Many of the features are reproduced. A more complete (and higher resolution) set of maps were made by the German x-ray satellite RoSat.


RASS 1/4 keV Band
counts/s/arcmin^2
0.00020
0.00040
0.00060
0.00080
0.00100
0.00120
0.00140
0.00160
0.00180
UW
SAS-3
HEAO-1 A2
5
10
15
20
25


RASS 3/4 keV Band
counts/s/arcmin^2
0.00010
0.00020
0.00030
0.00040
0.00050
0.00060
0.00070
0.00080
0.00090

Spatial structure of the X-ray Background: the maps

- At medium energies of 3/4 keV (wavelengths ~ 1 nm), the map is remarkably flat (outside the central region). The galaxy might absorb the x-rays from the bright bubble in the equatorial region.
- At low energies of 1/4 keV (wavelengths of 4.2 — 8 nm), the sky is bright at high latitudes and dimmer at low latitudes.
- It is not, however, dark, even at low latitudes where there's plenty of gas in our Galaxy to absorb any x-rays coming from beyond.
- *There must be a local source of x-rays*.
- What they found is like a doctor x-raying a patient expecting to see bones as shadows and seeing them bright instead (as if the patient ingested enough radioactive material to be lethal).

This is where I came in.

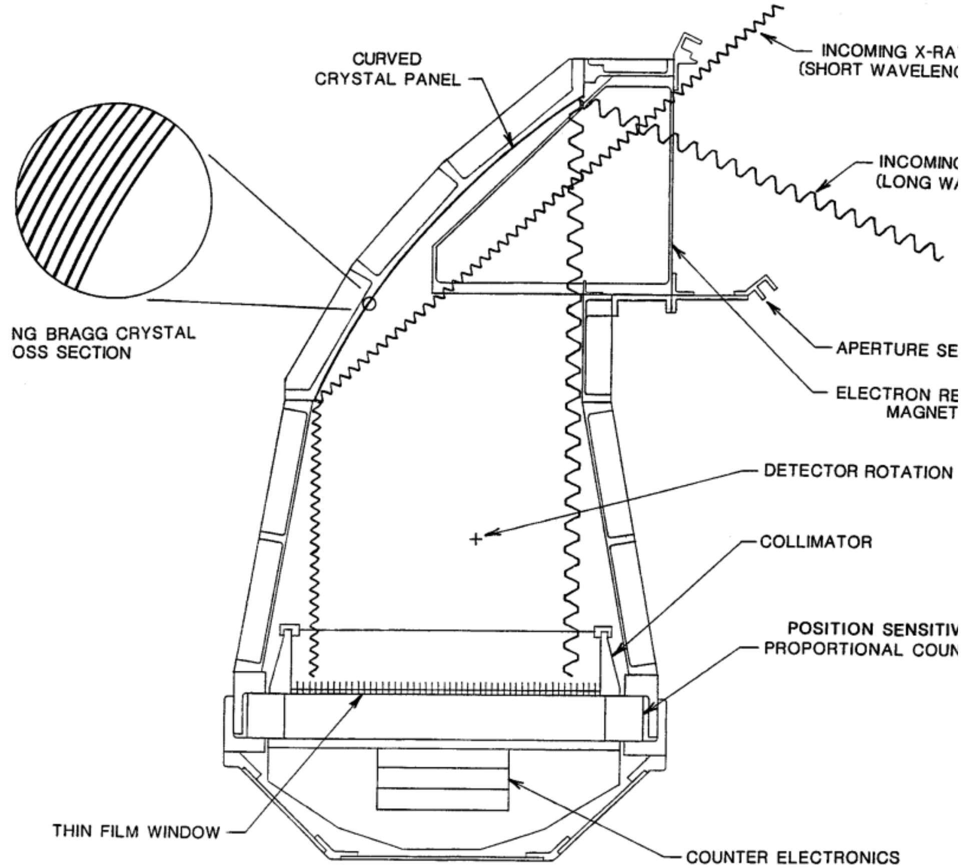
- The million K gas I talked about above could be a source of those x-rays.
- Some other ideas include various ways relativistic electrons can make x-rays, but they were ruled out because they would also have other observable effects (e.g. in the radio) which were not seen.
- There is a volume of this hot gas surrounding the solar system, with a radius of about 100 parsecs (300 light years). It’s taller than it is wide, almost as if a supernova went off nearby and blew a hole in the interstellar gas.
- My thesis made models of just such an event, and predicted x-ray spectra. I got it to match the broad-band x-ray observations that existed at the time.
- Note: A blast wave implies high pressure; probably not observed.

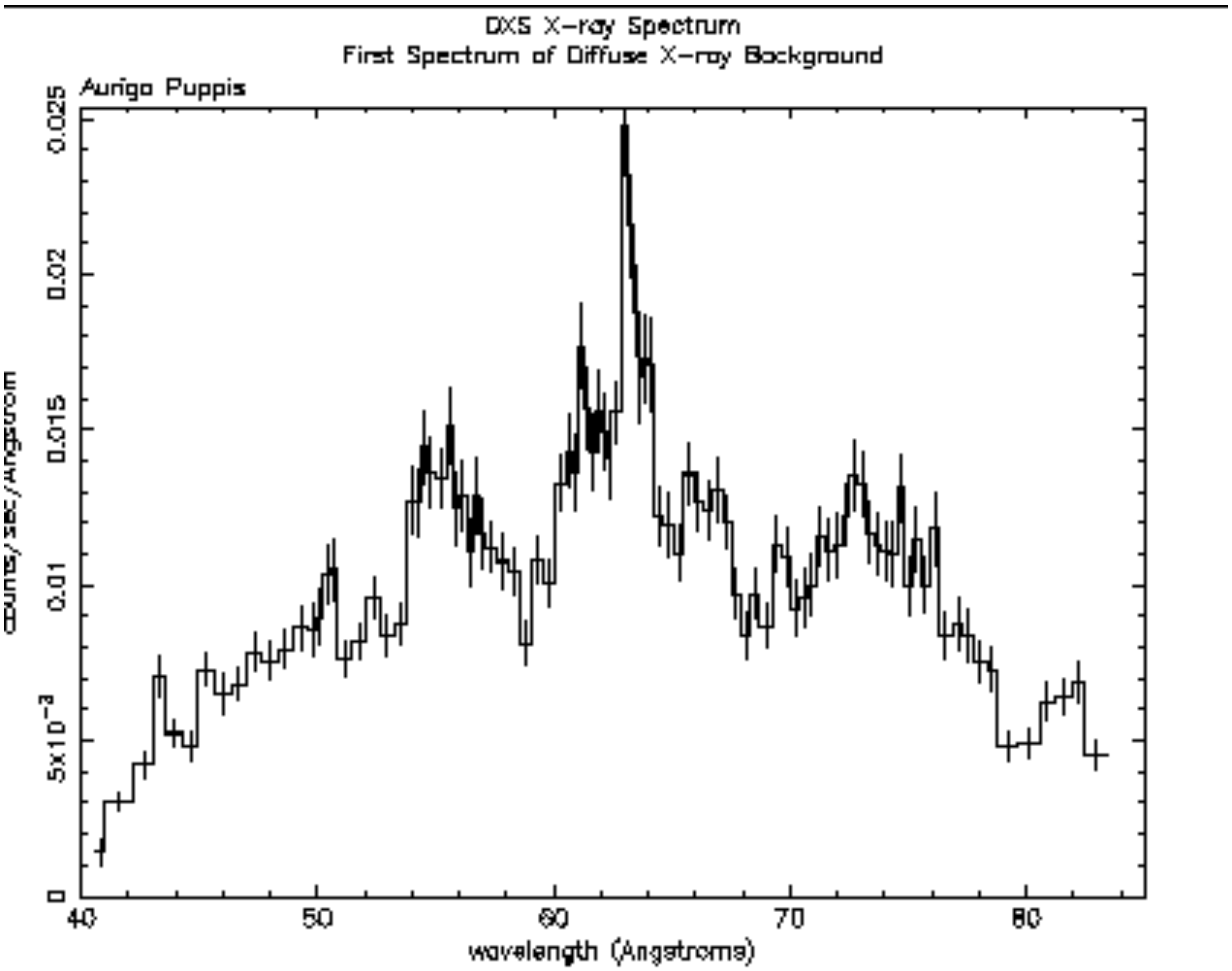
When in doubt, take a spectrum!

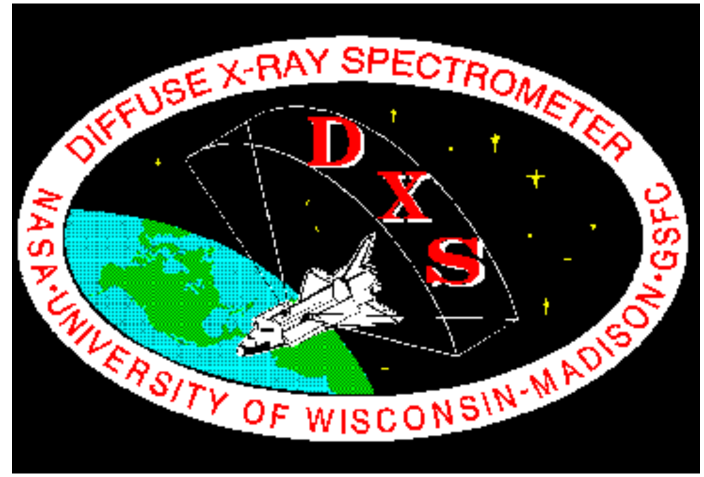
- Kraushaar (and after he retired, Wilt Sanders) and McCammon designed and built the Diffuse X-ray Spectrometer to measure the spectrum of the 1/4 keV diffuse x-ray background.
- It flew on a sounding rocket as proof of concept. In 5 minutes observing they probably saw lines.
- We refurbed it and interfaced it to the Space Shuttle, where it flew as an attached payload on mission STS-54 in January 1993.
- DXS is a large area (multiple square feet) Bragg crystal spectrometer with a field of view of 15 degrees square, and spectral resolution E/dE ~ 35.

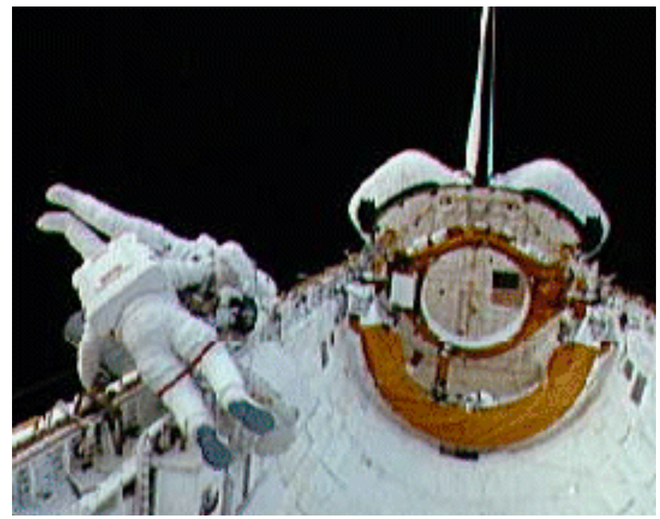
DXS instrument design

- Bragg reflection is efficient when the crystal layer spacing (100.5A) matches the projected wavelength of the x-rays
- A narrow range of angles are reflected for a given wavelength.
- Position-sensitive (1D) detector at bottom allows reconstruction of wavelength and incoming direction.
- Detector rotates about the + to build up coverage.




DXS X-ray Spectrum
First Spectrum of Diffuse X-ray Background
Auriga Puppis
counts/sec/Angstrom
0.025
0.02
0.015
0.01
5x10^{-3}
0
40
50
60
70
80
wavelength (Angstroms)

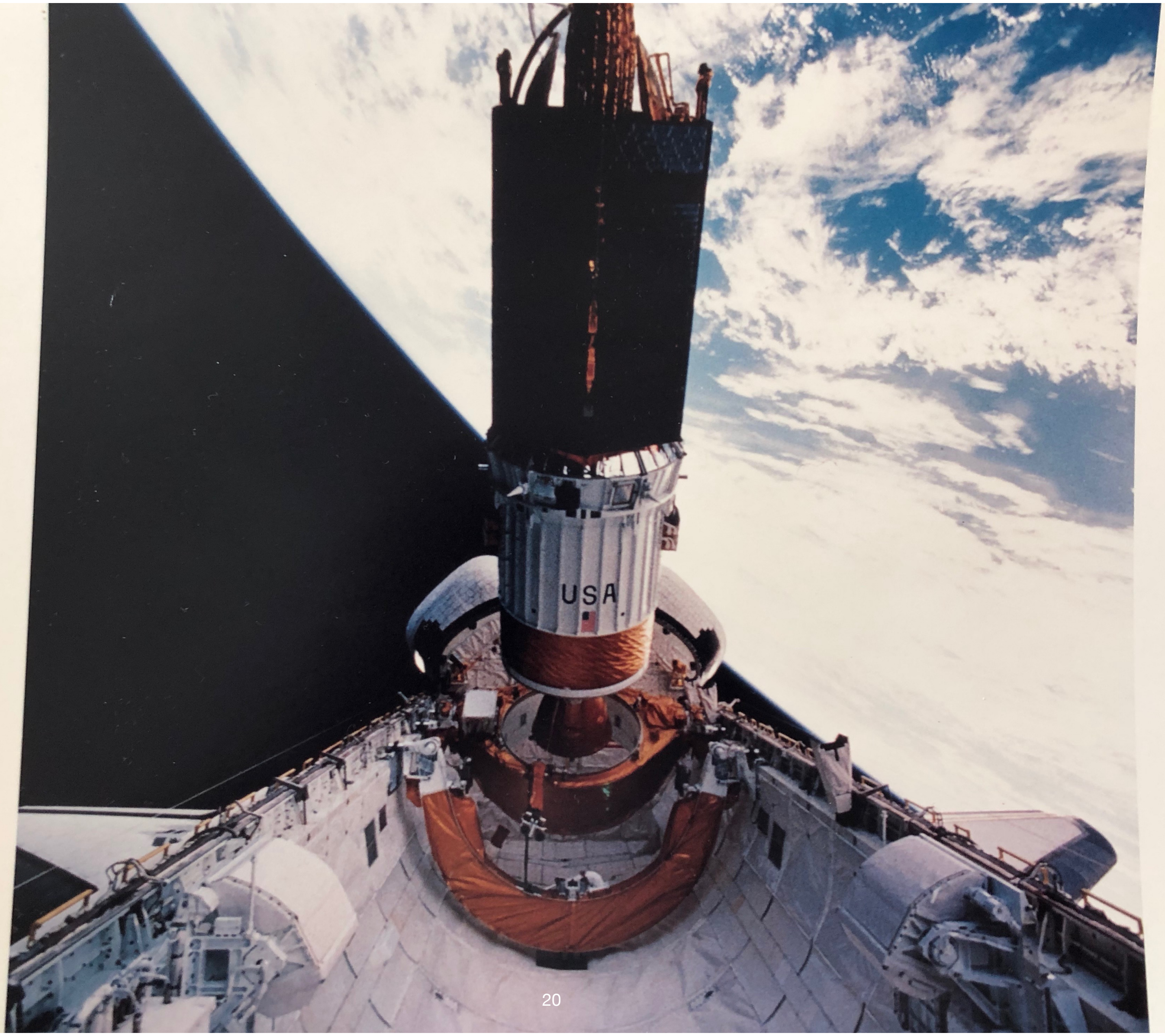

DIFFUSE X-RAY SPECTROMETER
DXS
NASA·UNIVERSITY OF WISCONSIN-MADISON·GSFC




The National Aeronautics and Space Administration
flew this United States flag aboard
the Orbiter Endeavour, STS-54, January 13-18, 1993
Presented to
Richard Edgar
CASPER McMONAGLE
RUNCO
HELMS HARBAUGH
In recognition of the significant contribution
made in furthering the development
and successful operation of the
Diffuse X-Ray Spectrometer (DXS)
on the STS-54 Mission.
Chris Dunker
DXS Mission Manager
DIFFUSE X-RAY SPECTROMETER
DXS
NASA·UNIVERSITY OF WISCONSIN-MADISON·GSFC

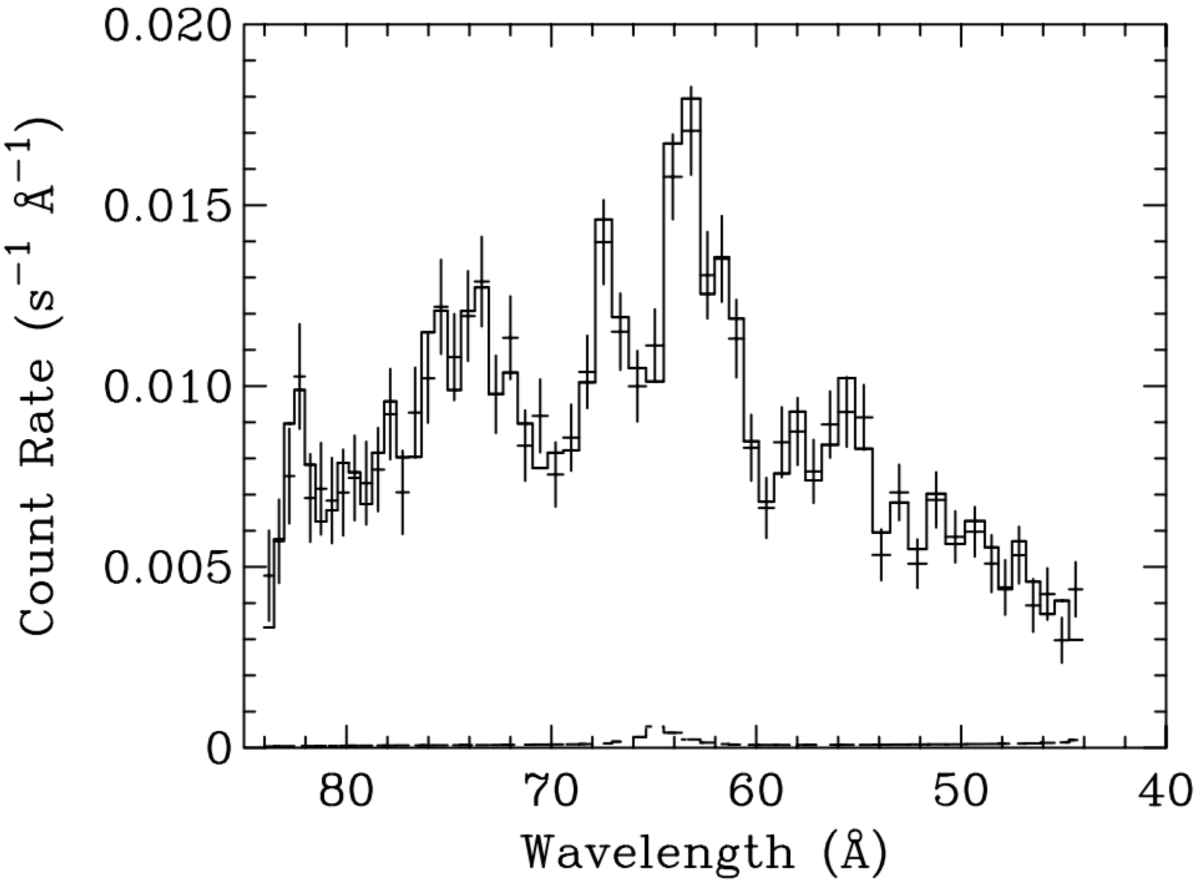
National Aeronautics and
Space Administration

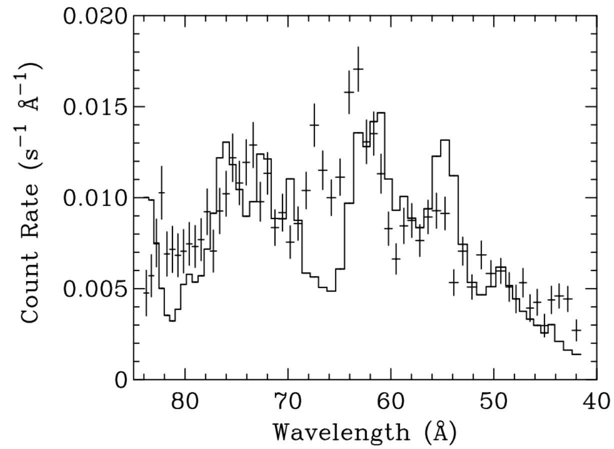
**Crew of Space Shuttle
Mission STS-54**

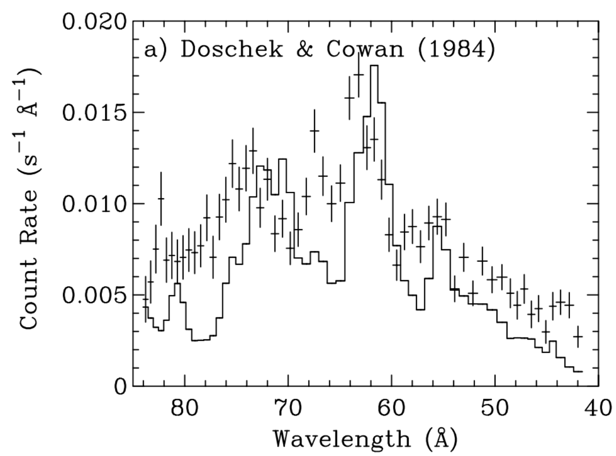

USA

First look at the data

- There are emission lines in the spectrum. This was expected but this is the first time they'd been observed.
- Attempts to fit hot gas models (either equilibrium or blast waves like my thesis) to this spectrum failed.
- Atomic physics for the relevant ions is in poor shape (but improving).
- Expect to see things like Mg^{+7}, Ne^{+7}, Si^{+7}, S^{+7}, Ar^{+8}, Fe^{+10} …
- Lines are blended together at this resolution.
- One bump consistent with an isolated spectral line (at 67.4 A) could be O^{+7} *n*=5->2 transition…


0.020
0.015
0.010
0.005
0
80
70
60
50
40
Count Rate (s^{-1} Å^{-1})
Wavelength (Å)


0.020
0.015
0.010
0.005
0
80
70
60
50
40
Count Rate (s^{-1} Å^{-1})
Wavelength (Å)

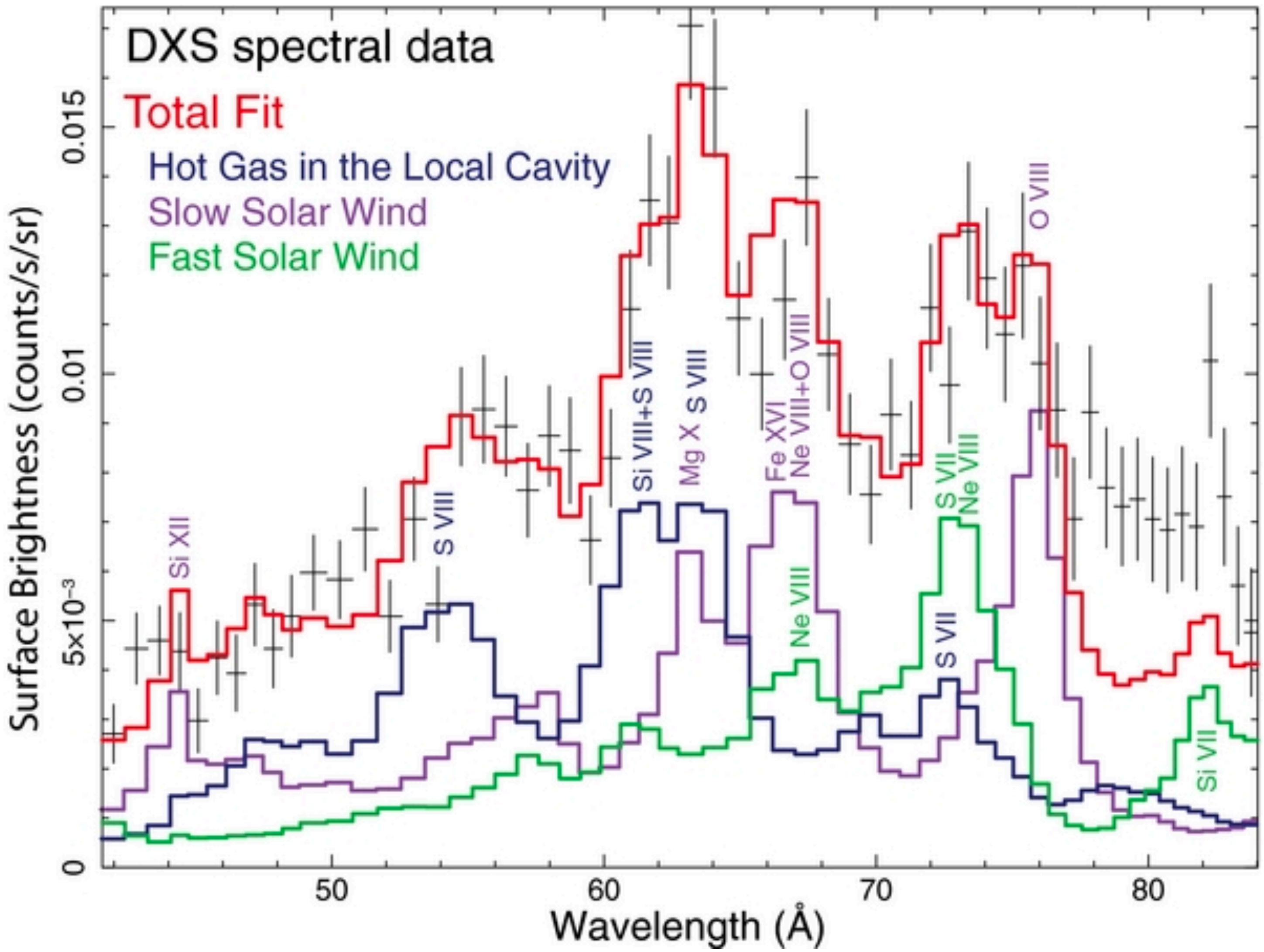

a) Doschek & Cowan (1984)
0.020
0.015
0.010
0.005
0
80
70
60
50
40
Count Rate (s^{-1} Å^{-1})
Wavelength (Å)

Wait for serendipity

- Here things stood for years.
- A long-shot target-of-opportunity RoSat observation of a comet turned up a process we had neglected in our proof by elimination
- Reactions between highly ionized elements in the solar wind and neutral atoms by “charge exchange” (electron goes home in a different atom) can produce x-rays
- $O^{+8} + H^{0} \longrightarrow O^{+7*} + H^{+} \longrightarrow O^{+7} + H^{+}$ + x-ray
- This particular reaction pumps the n=5 level in O^{+7}.

Solar Wind Charge Exchange

- The solar wind has lots of high ions in it.
- The heliosphere & solar system are embedded in an interstellar cloud, temp about 10,000 K, density 0.1 atoms / cm^3, partly ionized, scale 10 light years.
- Neutral H and He from that cloud can flow freely through the heliosphere, ignoring the magnetic disturbance at the bow shock.
- Simple models show you get about the right brightness of x-rays.
- Atomic physics proved difficult to either measure or calculate
- Some useful approximations were made…



DXS spectral data
Total Fit
Hot Gas in the Local Cavity
Slow Solar Wind
Fast Solar Wind
Si XII
S VIII
Si VIII+S VIII
Mg X
S VIII
Fe XVI
Ne VIII+O VIII
Ne VIII
S VII
Ne VIII
S VII
O VIII
Si VII
Surface Brightness (counts/s/sr)
0
5×10⁻³
0.01
0.015
50
60
70
80
Wavelength (Å)

It fits! But at what cost?

- Lots of knobs to twiddle…
- Three components:

1. Slow solar wind + interstellar neutrals;
2. Fast solar wind + interstellar neutrals; and
3. Hot bubble (as in my thesis).

- All parameters reasonable. The pressure in the hot bubble is even compatible with elsewhere in the interstellar medium.
- There's still some emission around 80 angstroms that's unexplained.

Lessons Learned

- Space astronomy can be fun!
- DXS got me another job… Tune in another time for a talk about the Chandra X-ray Observatory and operation of satellites.
- If you're going to argue by process of elimination, be very sure everything is on the table (we missed Solar Wind Charge Exchange in the 1980s).
- Spectral resolution is important! More more more more.
- But if you sort finite numbers of photons into too many bins, you get noise.