Modeling the Local Bubble With Supernova Remnant(s):

An Attempt to Match Theory to Observations

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I. Local Bubble Observations
II. Previous Models of the Local Bubble
III. Hydrodynamic Models
IV. Analytic Approximations for Superbubbles
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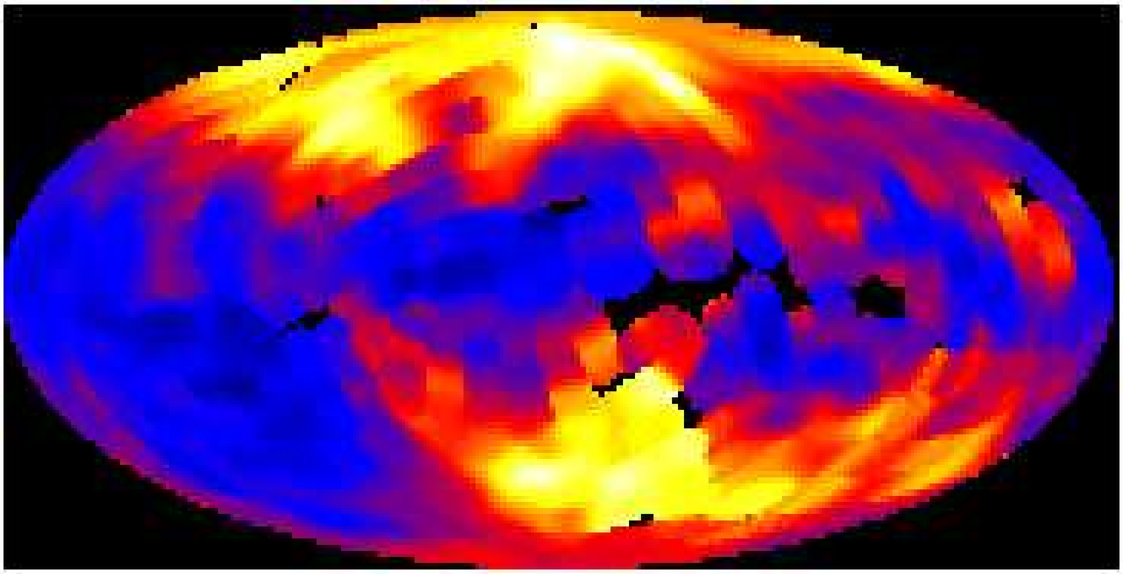
The goal of this work is to model the soft ($\leq 1\,\mathrm{keV}$) x-ray background using a few supernova remnants exploding in series in a homogeneous ISM.



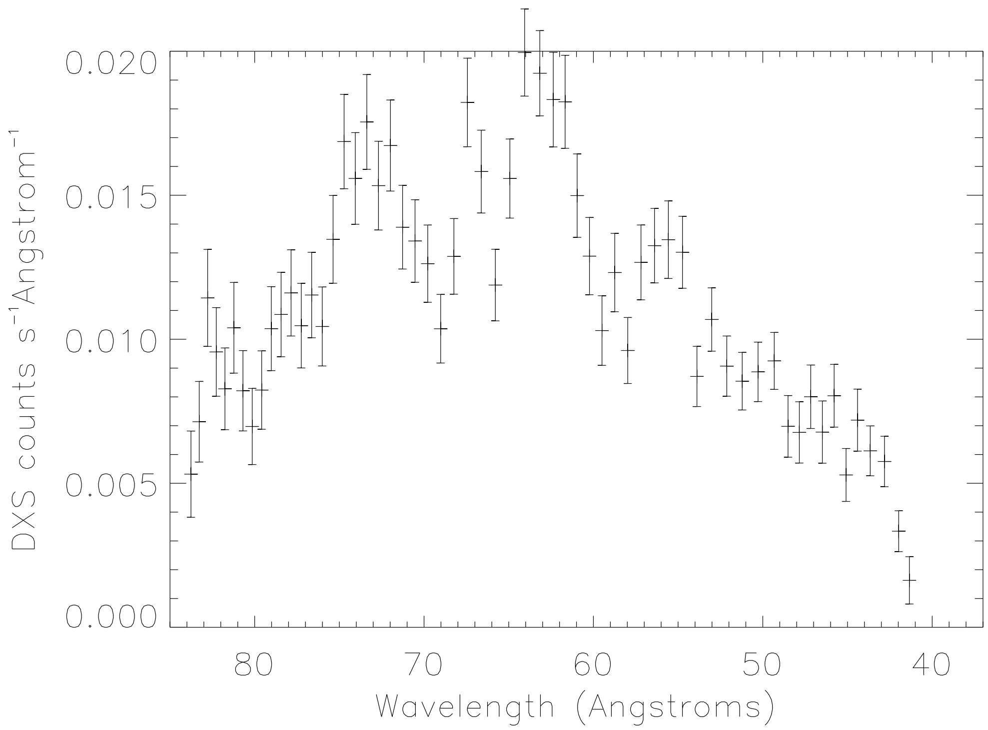
UW C Band All-Sky Survey

This talk describes work done with Dr. Donald P. Cox

Soft ($E < 1.0\,$keV) X-rays are observed in all directions. The intensity in the halo is $3-5\times$ that in the plane.

Data Source	Band	Observed $\lvert b\rvert < 10°$	Observed $b > 65°$	Observed $b < -65°$
UW Survey	B	40	75	45
UW Survey	C	95	180	140
UXT	Be	4.5	9	3.5
UXT	B'	7.5	16	13
ROSAT Survey	R1+R2	350	1145	410

DXS Observation of Puppis Region



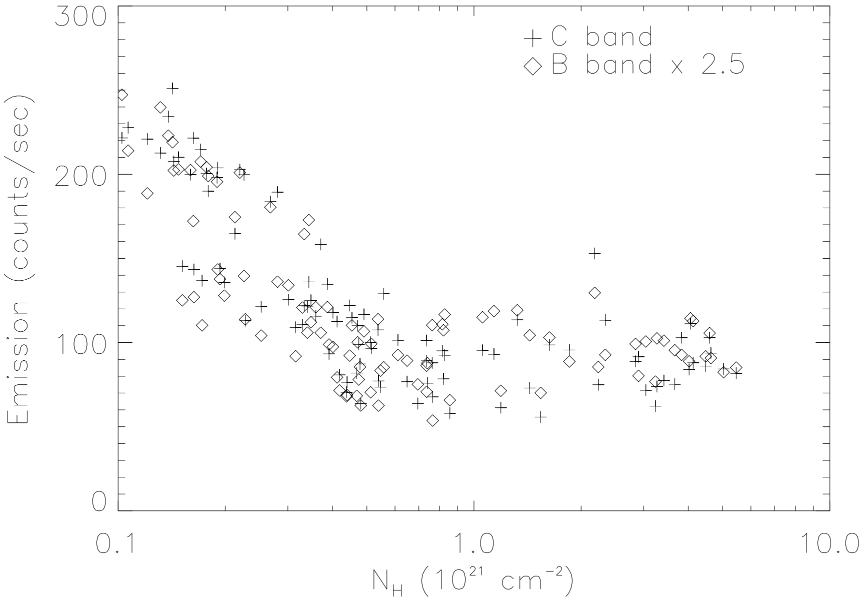
The existence and characteristics of the LB can be inferred through other observations, not just direct measurements of soft X-rays.

UV observations of local stars show that we are surrounded by a hole in N_H which extends approximately 100 pc, although towards the Galactic Center there exists substantial N_H within 30 pc.

Shelton & Cox (1994) used *Copernicus* measurements of O stars to measure the amount of O VI in the Local Bubble interior and edge. They found the best fit to the data required a Local Bubble component of:

$$N_{\mathrm{OVI}} = 1.6 \times 10^{13} \mathrm{cm}^{-2}$$

X-ray observations towards clouds in the Local Bubble using ROSAT and EUVE can be used to estimate the thermal pressure in the Bubble, assuming the spectrum is thermal. Snowden *et al.* (1993) found $P/k = 12500\,\mathrm{cm}^{-3}\mathrm{K}$ towards MBM 12, and Bowyer *et al.* (1995) found $P/k = 19000\,\mathrm{cm}^{-3}\mathrm{K}$.



The anti-correlation between the soft X-rays and the neutral hydrogen in the Wisconsin data suggested a simple foreground plus absorbed background model:

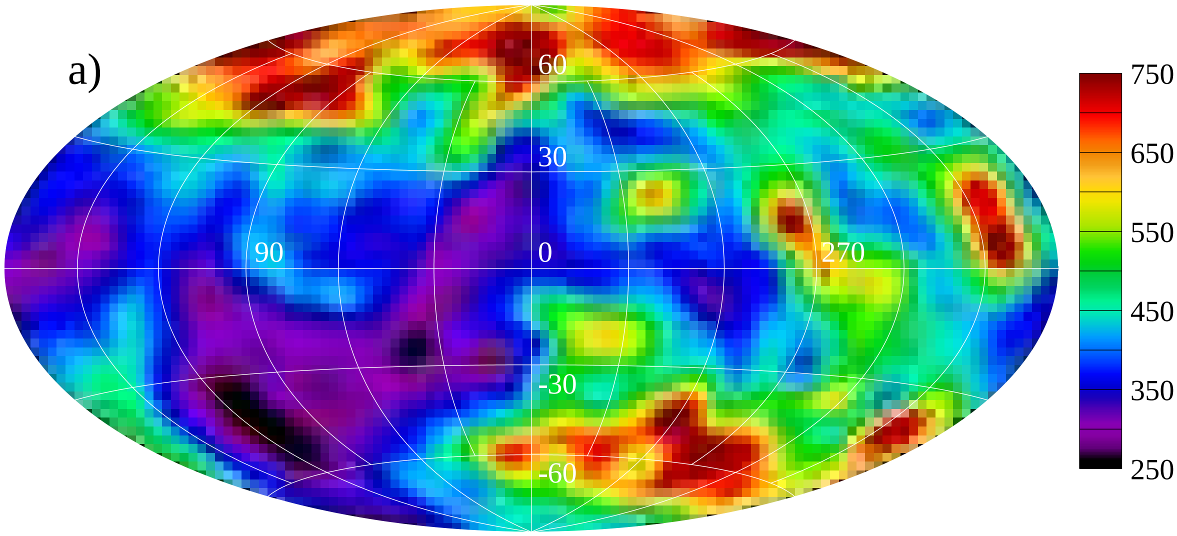
$$I_{X-ray} = I_{\rm fg} + I_{\rm bg} e^{-\sigma(E) N_H}$$

But $\sigma(E)_{\rm fit} \neq \sigma(E)_{\rm calc}$. This implies absorption is not the primary cause of the anti-correlation.

However, the anti-correlation can also be explained by the displacement model.

The neutral hydrogen layer of the Galaxy has a $\sim$ 100 pc scale height. So a cavity of similar size would "displace" the neutral material and lead to the observed anti-correlation.

R1+R2 BAND I0 INTENSITY



Recent ROSAT measurements have found conclusive evidence for absorption towards selected regions.

This plot (from Snowden *et al.*, 1997), shows the foreground emission in the R1+R2 bands after fitting the entire dataset to an absorption model. Even after removing external sources, there is still leaves a substantial local component, which retains a halo/plane asymmetry. The "displacement" model, or some substitute, is still required.

Plot courtesy Steve Snowden; ROSAT all-sky survey data courtesy of MPE.

The simplest displacement model assumes the LB is filled with a single-temperature gas in collisional ionization equilibrium. Then, intensity is proportional to length of sight-line. This model was codified in Snowden *et al.* (1990) (SCMS), with the following parameters:

Quantity	Material Removed	Material Swept Out
Plasma emissivity (B counts $s^{-1}pc^{-1}$)	0.48	0.30
Electron density (cm^{-3})	0.0047	0.0037
Plasma temperature (K)	$10^{6.0}$	$10^{6.0}$
Thermal pressure (p/k; $cm^{-3}K$)	9000	7100
Radius of sphere (pc)	118	185
Surface Area (cm^2)	1.4×10^{42}	3.5×10^{42}
Stored energy (ergs)	3.7×10^{50}	11.3×10^{50}
Radiative Lifetime (yr)	2.3×10^{7}	3.0×10^{7}
OVI column density (cm^{-2})	5.1×10^{12}	6.3×10^{12}

These results, however, used the 1977 and 1984 versions of the Raymond & Smith code. The latest 1993 update has substantial differences in spectral shape and intensity for a 10^6 K plasma.

Release year	B band	C band	R1+R2
1984	2.035×10^4	4.793×10^4	2.880×10^5
1984a	2.036×10^4	4.794×10^4	2.881×10^5
1987	1.503×10^4	3.766×10^4	2.240×10^5
1992	1.133×10^4	2.628×10^4	1.585×10^5
1993	1.133×10^4	2.628×10^4	1.585×10^5

As a result, the original displacement model is under-luminous, due solely to changes in the plasma code. The 1993 revision requires electron densities and pressures that are $\sim \sqrt{2}$ larger than before:

Quantity	Material Removed	Material Swept Out
Plasma emissivity (B counts $s^{-1}pc^{-1}$)	0.27	0.17
Electron density (cm^{-3})	0.0063	0.0050
Plasma temperature (K)	$10^{6.0}$	$10^{6.0}$
Thermal pressure (p/k; cm^{-3}K)	12000	9500
Radius of sphere (pc)	118	185
Surface Area (cm^2)	1.4×10^{42}	3.5×10^{42}
Stored energy (ergs)	5.0×10^{50}	15.1×10^{50}
Radiative Lifetime (yr)	1.7×10^{7}	2.2×10^{7}
OVI column density (cm^{-2})	6.8×10^{12}	8.4×10^{12}

This model pressure is closer to the measurements $12,500 - 19,000 \mathrm{cm}^{-3}$K, and the value which will be necessary in my models.

Assuming the LB is a supernova remnant, a magnetohydrodynamic (MHD) code is necessary to model it. Our code, ODIN has the following features:

- One-dimensional Lagrangian mesh
- Evolves ionic abundances
- Variable initial conditions, including multiple explosions
- Thermal conduction, including saturation
- Spatially varying abundances
- Includes dust:
  - Cooling
  - Sputtering
- Output:
  - XSPEC-ready spectral calculations
  - Line intensities and widths
  - Column densities

Upcoming features will include the calculated infrared spectrum, dust formation in ejecta, and the integration with CLOUDY to do radiative transfer. The importance of a self-consistent treatment of particle acceleration will be investigated as well.

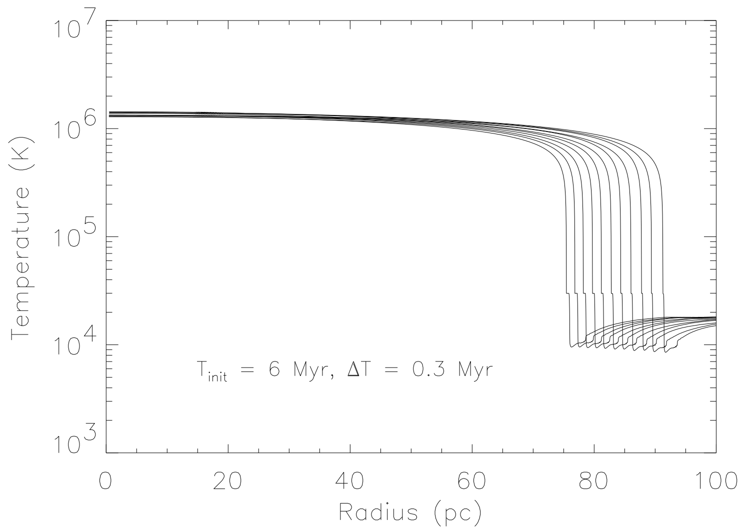
A hot LB model requires $R_B \sim 100\,\mathrm{pc}$ and $T_B \sim 10^6\,\mathrm{K}$. Models like this come in two flavors: active and old.

Active (age $\leq 10^5\,\mathrm{yr}$) SNR models: These fit the soft x-ray data (Edgar, 1986), but suffer from over-predicting the OIV abundance and velocity. In addition, the models require a pre-existing cavity.

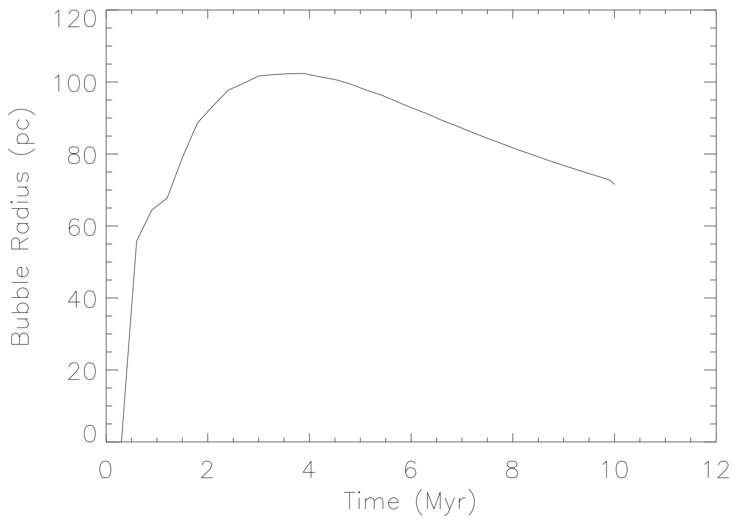
Old (age $\geq 10^6\,\mathrm{yr}$) SNR models: These models required a large initial supernova energy (5×10^{51} ergs) and ambient magnetic field ($\geq 8\mu$G), and generated overly soft X-rays (Edgar & Cox, 1993). As a result, they suggested...

Multiple SNR: The first SN creates a large cavity, with dense "walls." For normal SN, the interior gas temperature would be below 10^6K, generating too-soft X-rays. The second (or third) SN then re-heats the remaining material. Thermal conduction keeps the interior of the bubble from becoming too hot and diffuse.

The late-term evolution of multiple explosion models have many characteristic results. These were seen for a wide variety of model parameters. The temperature profile is self-similar:



And the bubble collapsed linearly:



We attempted to understand these models in an analytic framework. The two most successful we termed the "Differential Emission Measure" (DEM) method and the "Thermal Conduction Driven" (TCD) method.

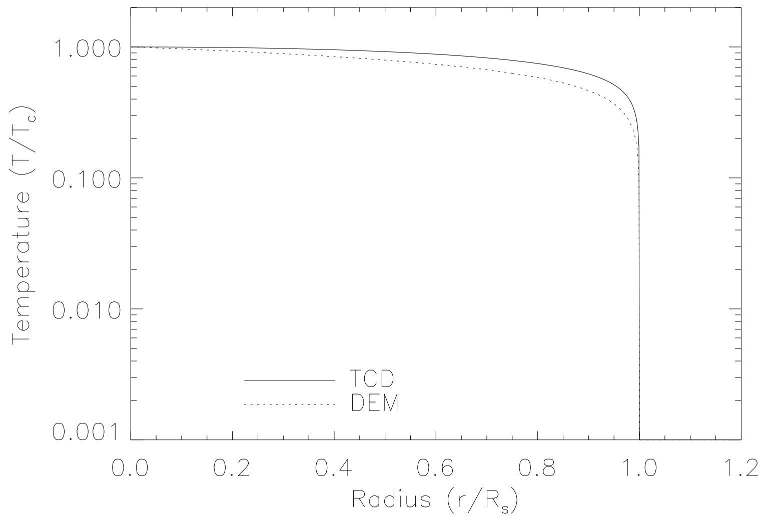
The DEM model is obtained by assuming that the thermal conduction flux ($\beta T^{5/2}\partial T/\partial r$) is balanced by radiative cooling ($n_e n_H \alpha T^{-1/2}$). Then the following can be derived:

$$\frac{n_e^2}{n_e T}\frac{dr}{dT} = \sqrt{\frac{\beta}{2\alpha}}$$

The TCD model is derived by ignoring cooling, requiring a stable bubble (dV/dt = 0) and assuming that energy lost only through thermal conduction flux ($4\pi r^2 F$). This is balanced by an source (SN) such

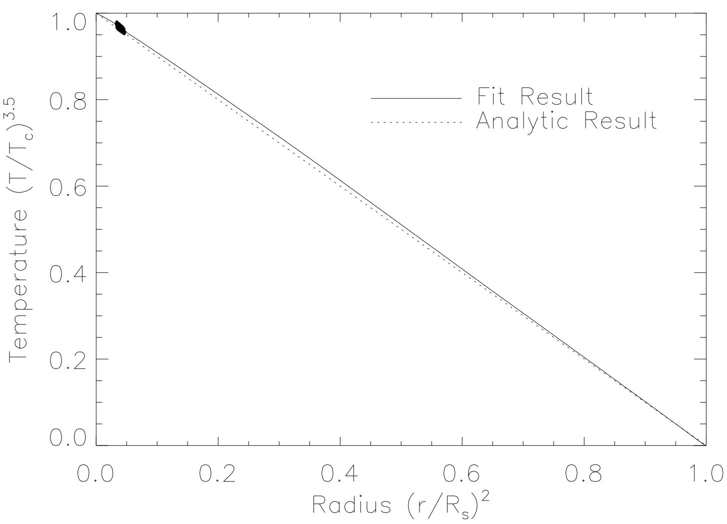
$$\frac{d}{dt}(\frac{3}{2}pV) \propto \frac{3}{2}pV$$

$$4\pi r^2 \beta T^{5/2}\frac{dT}{dr} \propto \frac{4\pi}{3}r^3 p$$



$$T(r)_{\mathrm{DEM}} = T_c(1 - (r/R_s))^{1/3}$$
$$T(r)_{\mathrm{TCD}} = T_c(1 - (r/R_s)^2)^{2/7}$$

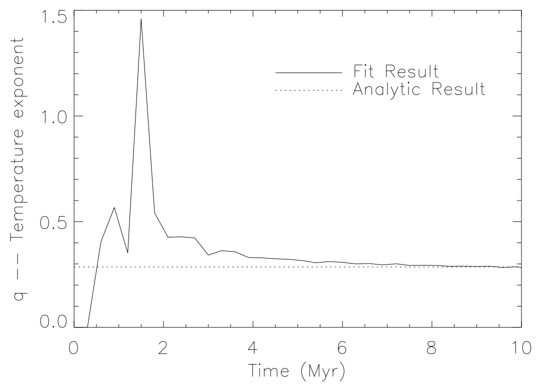
While the DEM model adequately approximated the final temperature drop, the TCD model fits the entire calculated temperature profile extremely well, especially at late times:

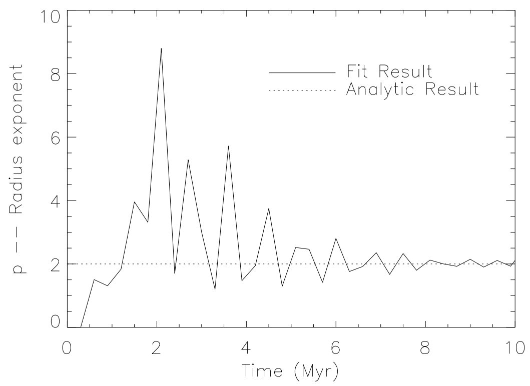


Once beyond simple models, a nearly overwhelming wealth of choices confront us. It is for this reason that the simple models, especially the simple TCD and DEM models, are so useful. Both the TCD and DEM models have the characteristic form:

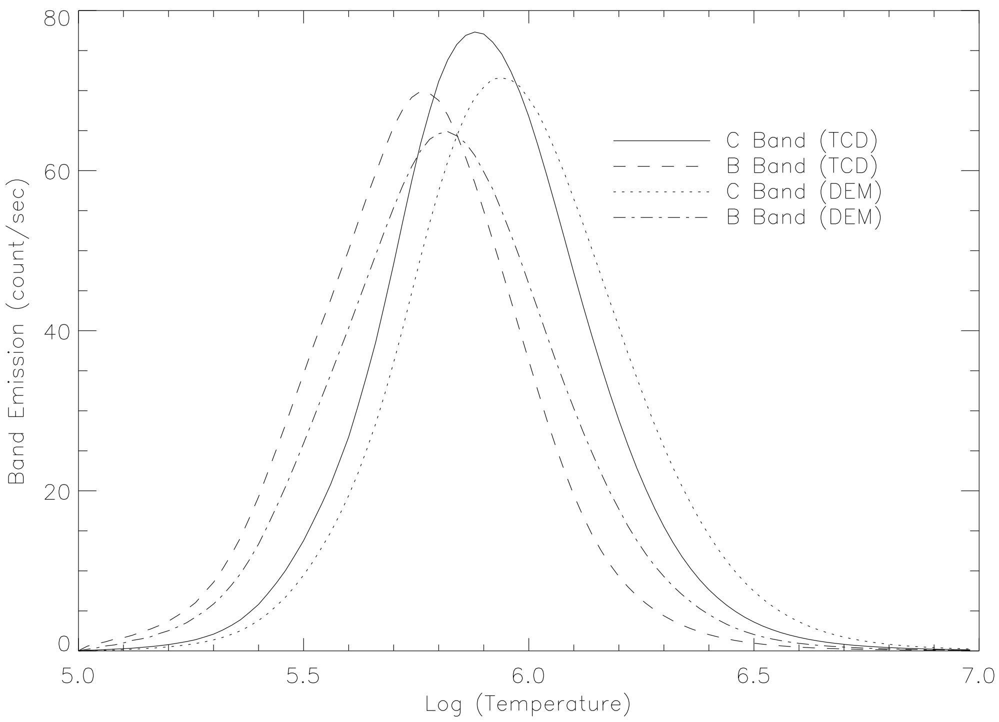
$$T(r) = T_c(1 - (r/R_s)^p)^q$$

The calculated temperature profile is fit extremely well when p and q are allowed to vary. For these plots, the central temperature T_c and bubble radius R_s are taken directly from the data, with the first cell defining T_c and the first cell at or below 3×10^4K defining the bubble edge. With these definitions, the fit parameters p and q tend to approach the TCD value over time:



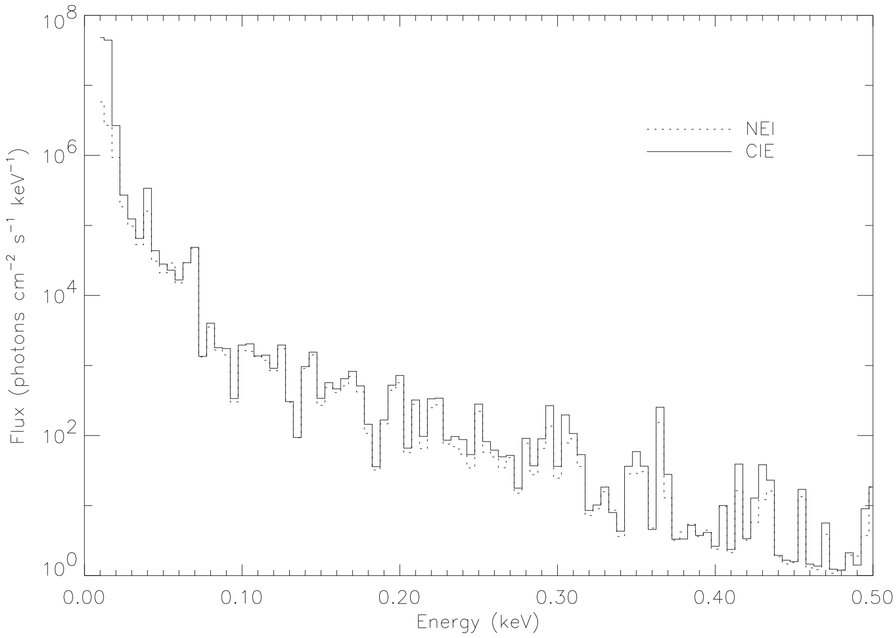


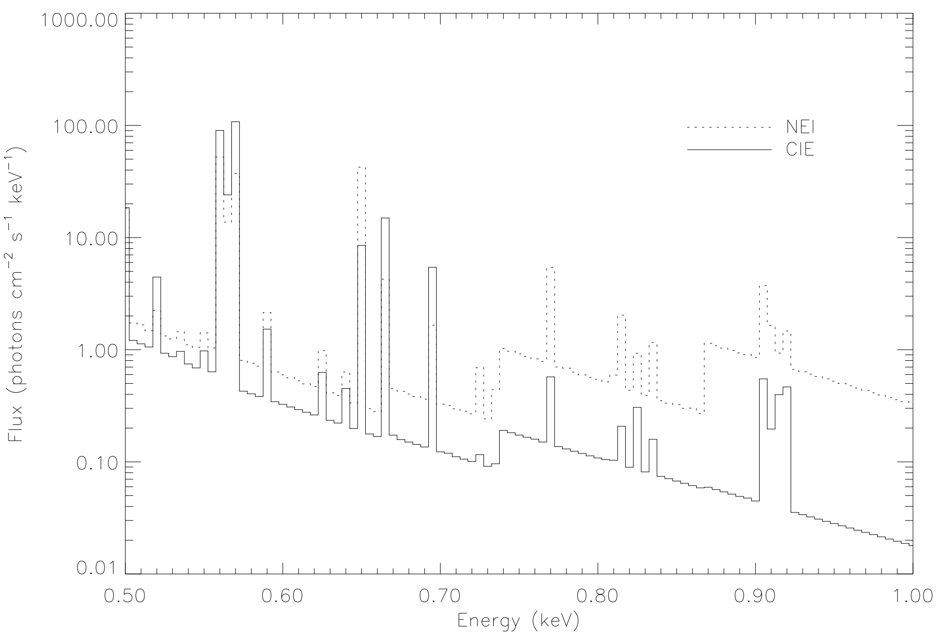
Given a central temperature (T_c), bubble radius (R_s), and ambient pressure (p/k), the X-ray emissivity of these models can be calculated in equilibrium. Shown here is the emission for a 100 pc bubble with an internal pressure of $10^4\,\mathrm{cm}^{-3}\mathrm{K}$, for a range of central temperatures:



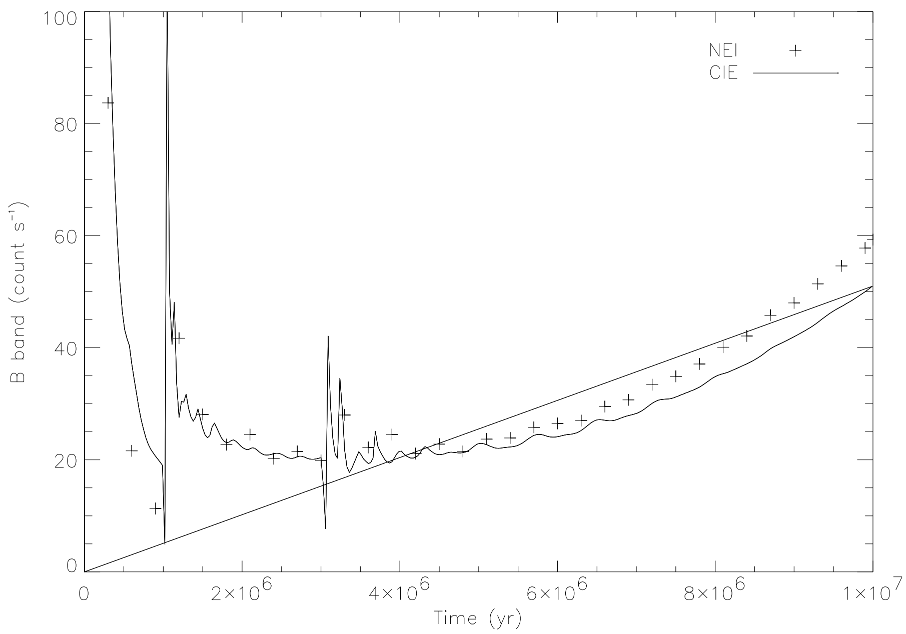
The emission scales linearly in radius and as the square of the pressure. Therefore, it is possible to find a temperature, bubble radius, and pressure that will match the observed B and C bands.

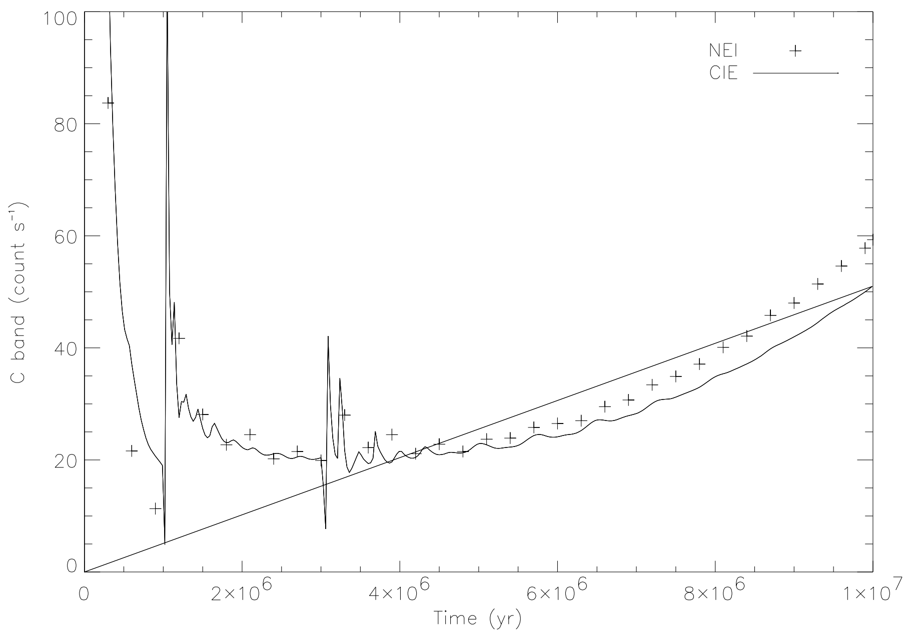
Is the gas is in or near collisional ionization equilibrium? At low energies yes, but not in higher bands:





We can see the same effect in the B and C bands, over time:



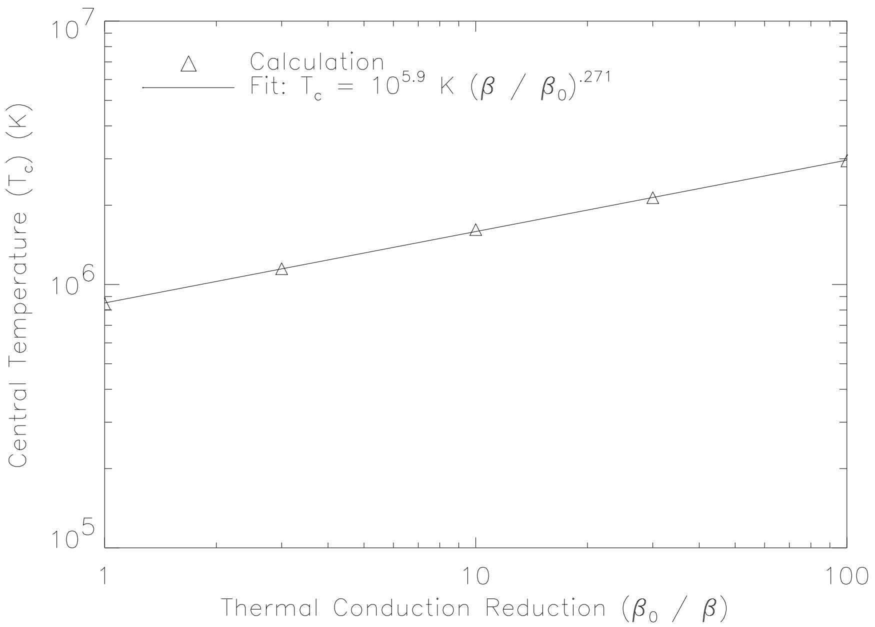


Therefore, if we can simply find a set of parameters which has the appropriate values of T_c, R_s, and p/k, we will get the correct B/C ratio.

We do not have an analytic model to describe $R_s(t)$, other than to note it seems to be linear at late times, with slope approximately -10 km/s. The same is true of the interior pressure, although it tends to be 1/2 to 2/3 of the external pressure.

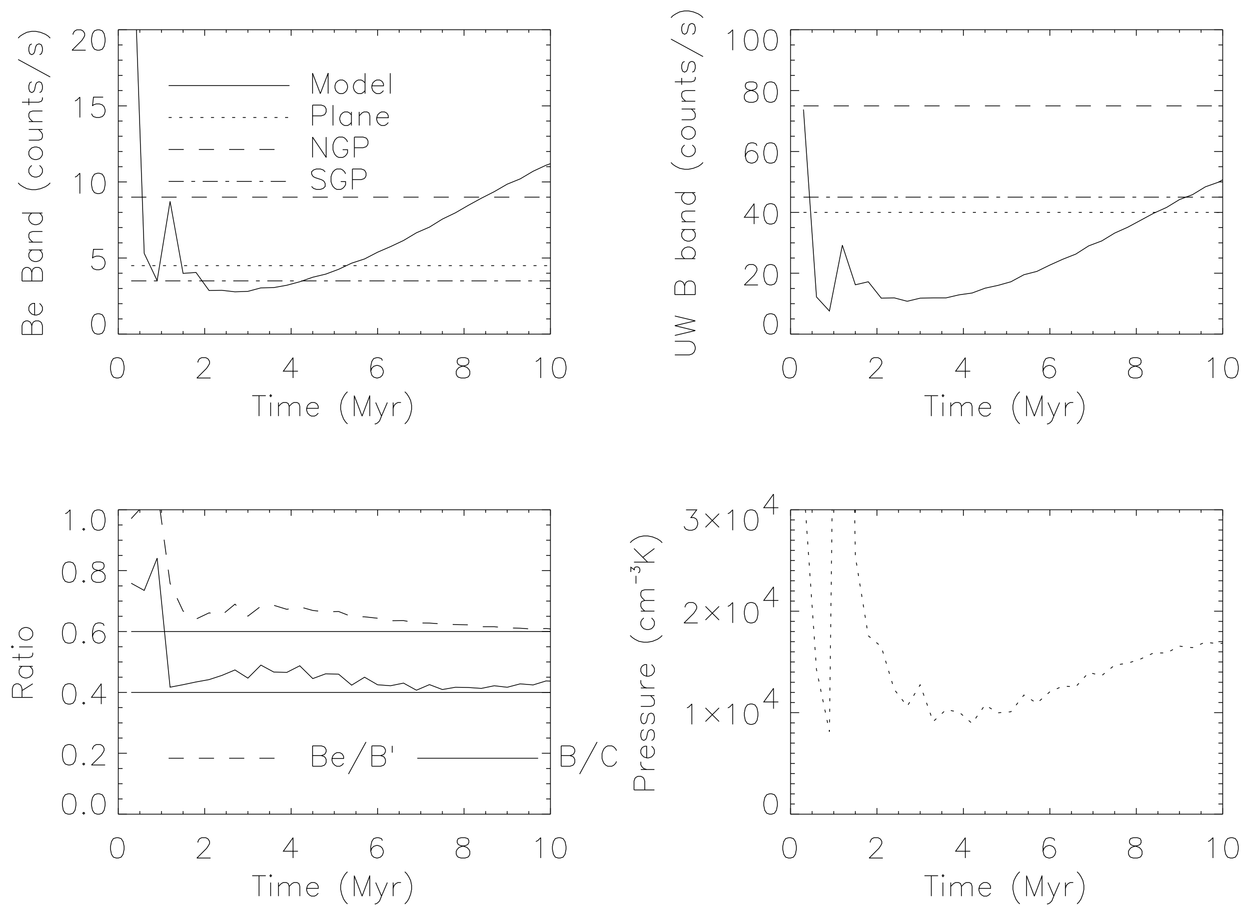
The central temperature, however, can be predicted using the TCD model to follow the form:

$$T_c = T_{c0}(\frac{\beta_0}{\beta})^{3/13}$$

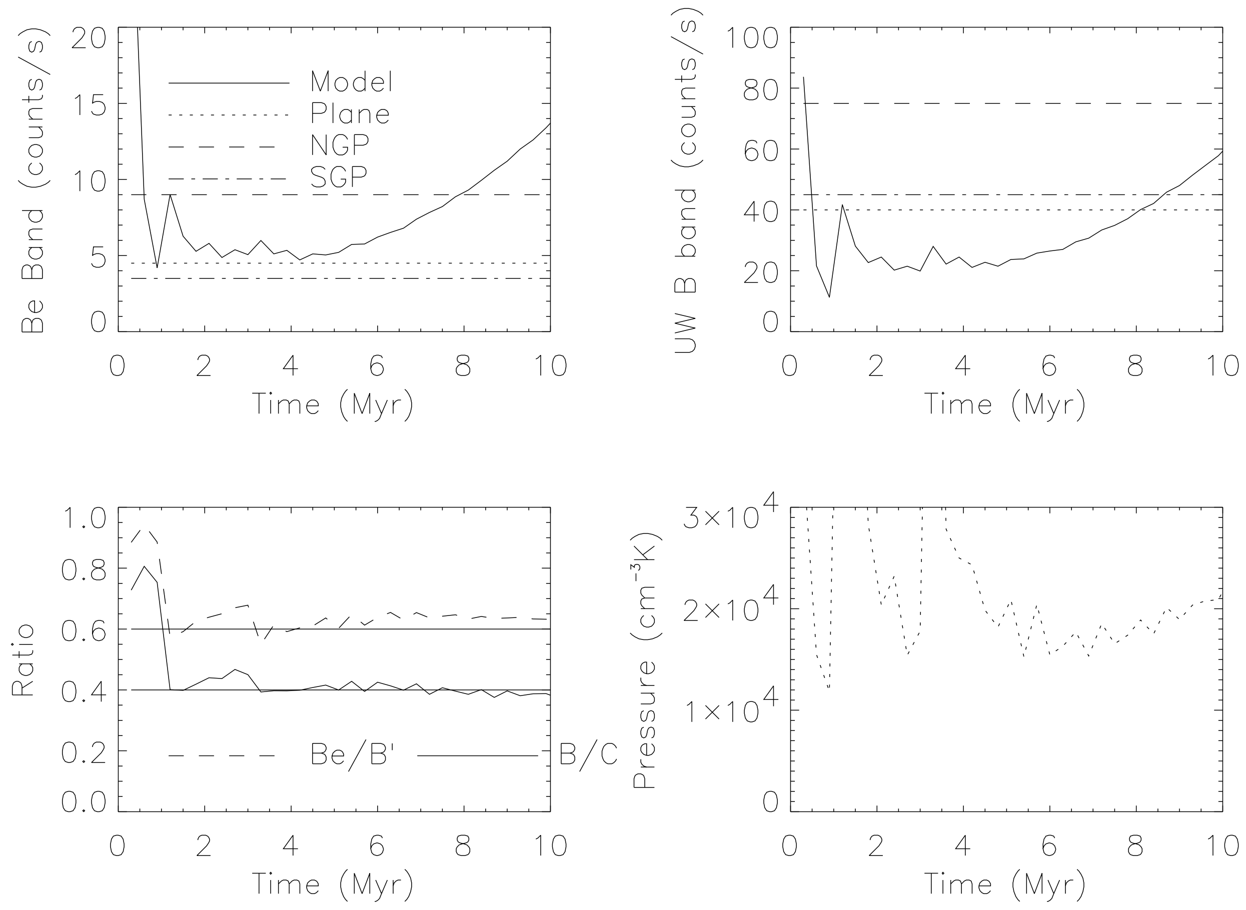


Model	N_{exp}	$n(cm^{-3})$	$E_{51}(10^{51}ergs)$	$\beta/\beta_{Spitzer}$	B (μG)	Result
A	2	0.2	1.0	1/6	5.0	Reasonable fit, 5-8 Myr
B	3	0.4	1.0	1/6	5.0	Reasonable fit, 5-8 Myr
C	2	0.2	0.5	1	5.0	Too soft and dim
D	3	0.2	0.5	1/30	5.0	Far too dim, but good ratios
E	3	0.4	1.0	1	5.0	Too bright, too soft
F	3	0.2	1.0	1	7.0	Too bright, too soft
G	3	0.4	1.0	1	7.0	Too bright, too soft

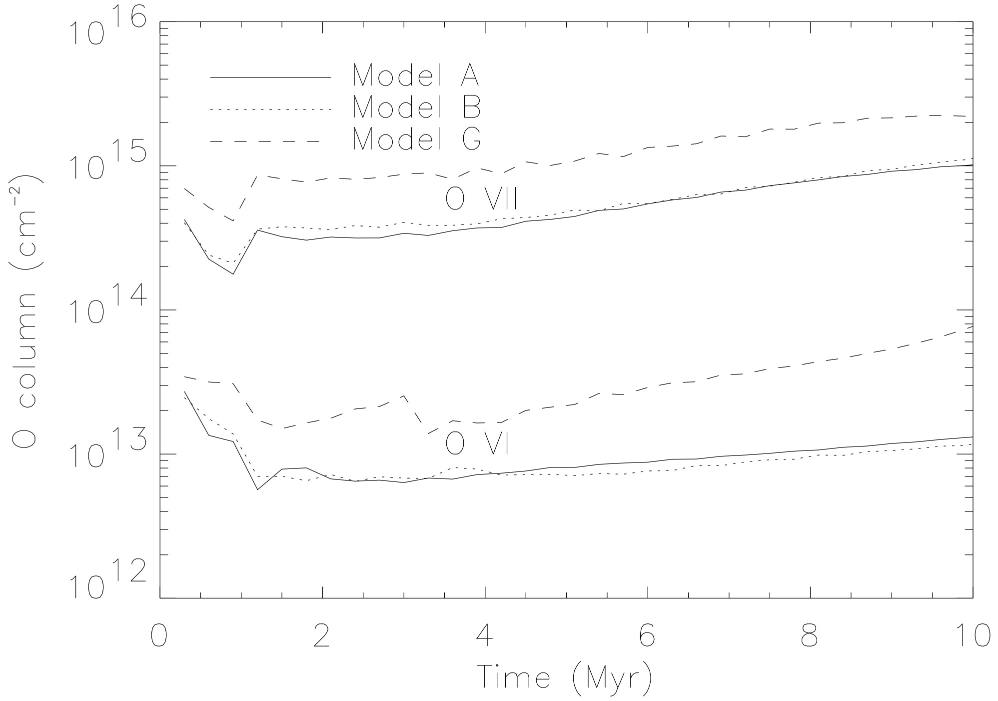
Characteristic plots from Model A are shown here:

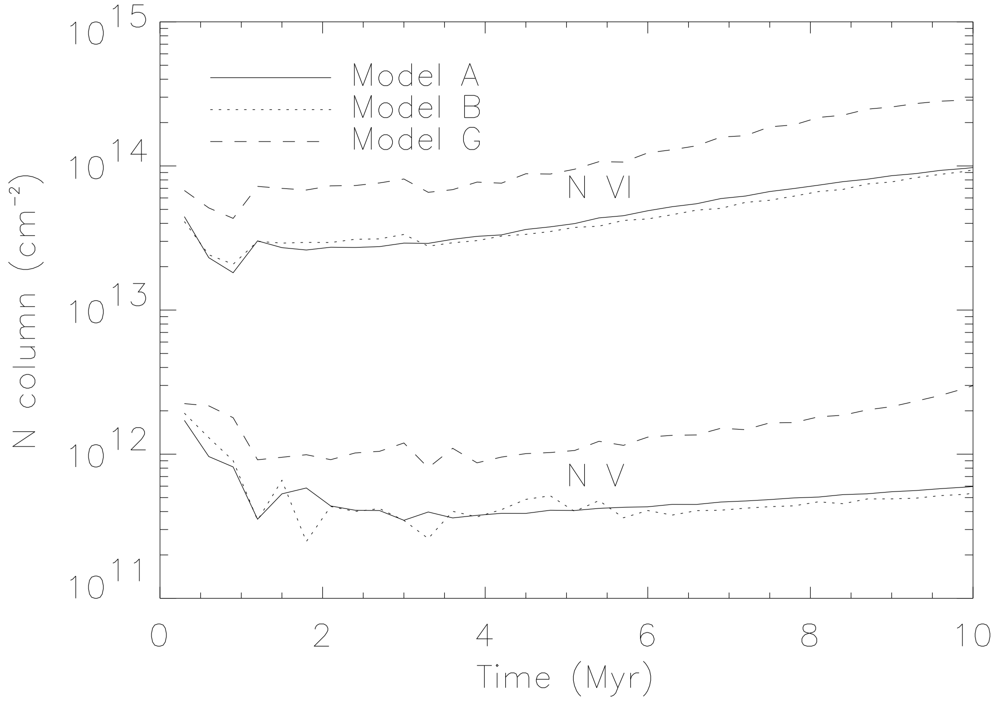


Model B is similar to Model A, but with 3 SN and a higher initial density, $0.4\,\mathrm{cm}^{-3}$:

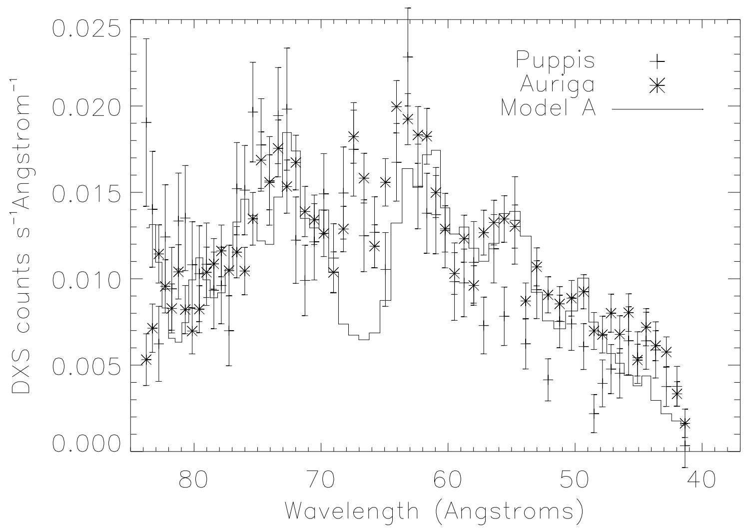


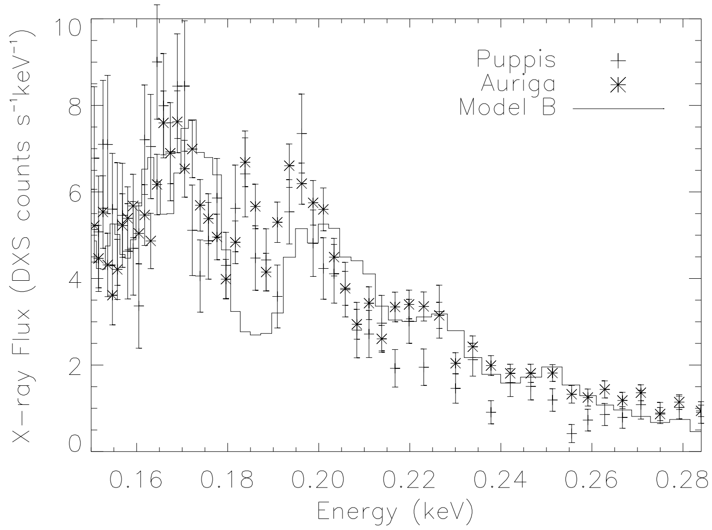
Column densities for Model A and B over time:





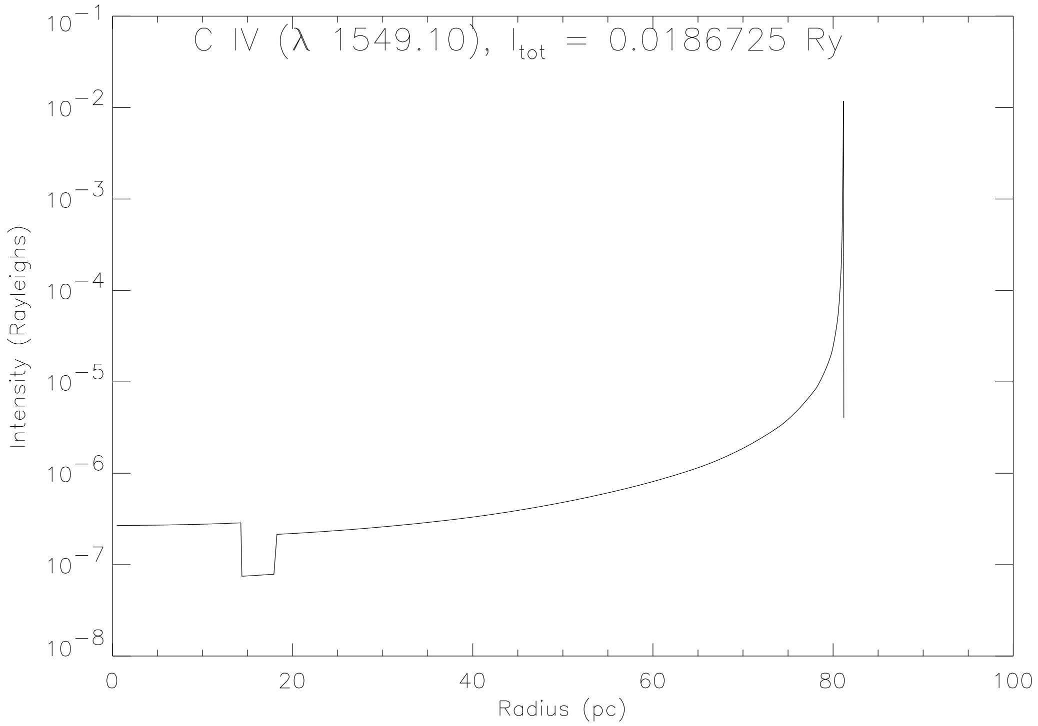
The models generate a spectrum that can be compared to the DXS results. Plotted here is the DXS measurement of the Puppis and Auriga regions, along with the Model A and B spectrum, both at 5.4×10^6 years:





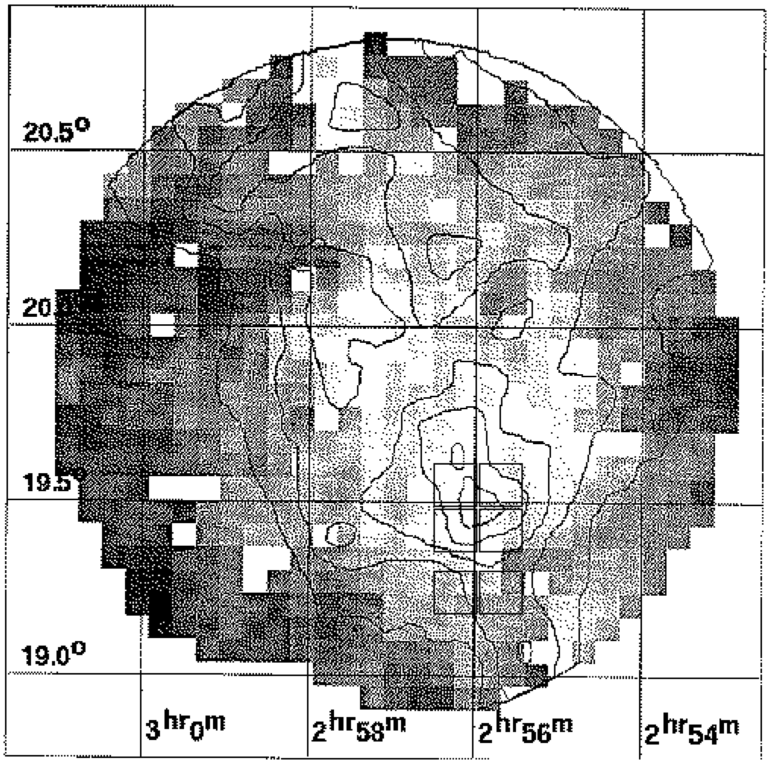
Data and response matrices courtesy Wilt Sanders, Dick Edgar, and the entire DXS team.

It is also possible to use the RS93 code to generate line strengths for individual lines. As an example, the diffuse C IV 1550Å line emission from Model A is:



The kink near 10-20 pc is due to the initial conditions–these cells were "ejecta" cells and cannot be compared to the general ISM.

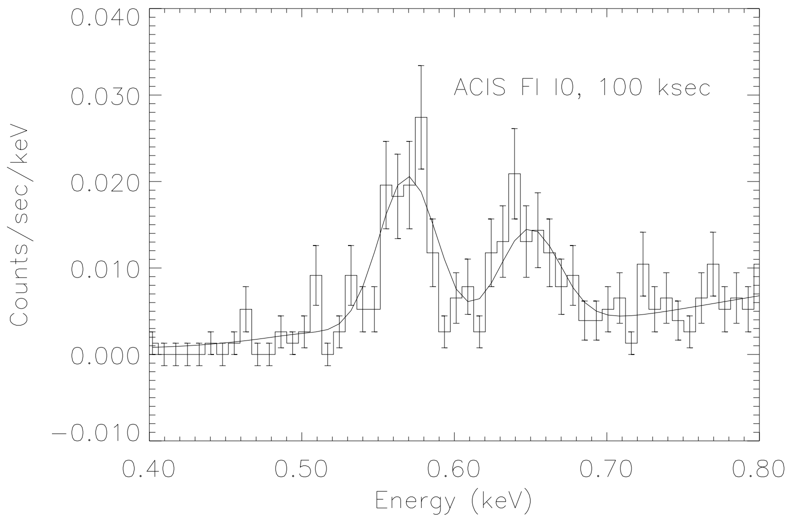
However, the majority of the emission comes from a single point, so this must be regarded as preliminary; higher resolution models need to be run. Nonetheless, this calculation could be done for any line–suggestions are welcome.



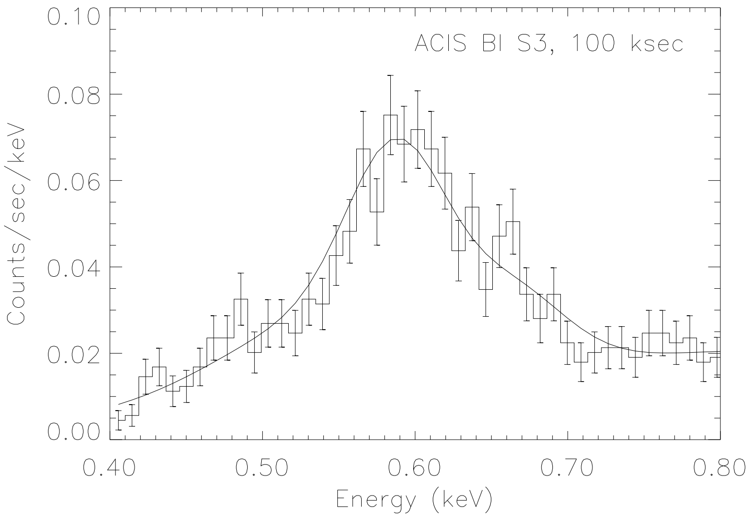
To observe **only** the diffuse emission from the Local Bubble requires an absorber that removes any background emission. The molecular cloud MBM12 serves this purpose well, as it is $60 \pm 30\,\mathrm{pc}$ distant and has a column density of $\mathrm{N_H} = 3.2 \times 10^{21}\,\mathrm{cm^{-2}}$.

ACIS-I field of view shown on the *ROSAT* PSPC 3/4 keV map, overlaid with the IRAS 100μm contours. The ACIS-I array is shown to scale, along with the S2 and S3 chips of the ACIS-S array. The minimum contour is 5 MJy/sr, going up to 25 MJy/sr at the center of the ACIS FOV.

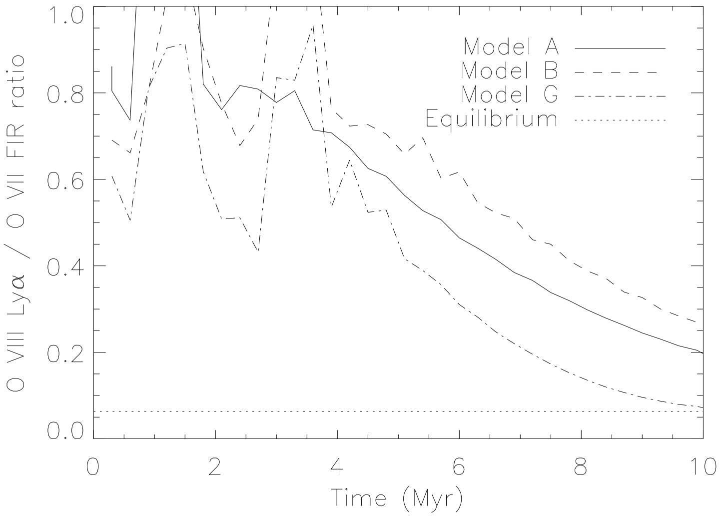
Sample spectrum from one FI chip with 100 ksec of the diffuse x-ray background, using the line intensity and power laws of Gendreau *et al.* (1995). Note how both lines are clearly detected.

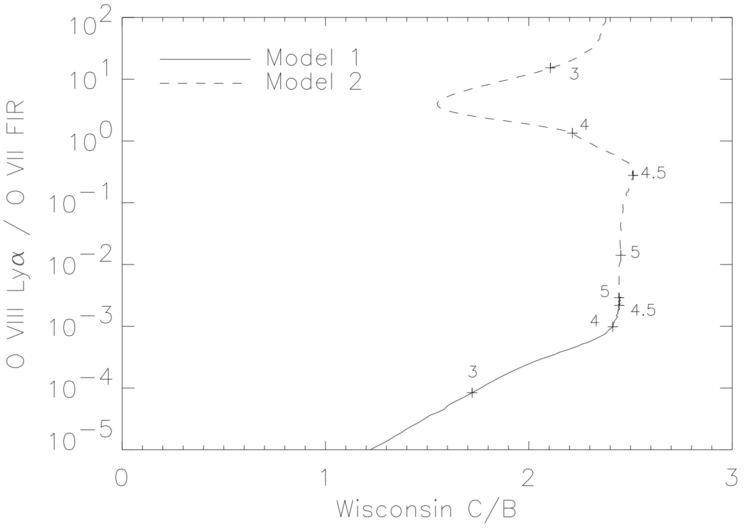


Same, for the S3 BI chip. Although the BI chip cannot resolve the lines itself, in combination with the FI chip it can get a better measurement of the overall power in the lines.



The Oviii/Ovii ratio as a function of fluence for two NEI models. Both cases held the electron temperature $T_e = 10^6$K, but in the ionizing case the ions are initially in CIE at $T = 10^4$K, while in the recombing case they are in CIE at $T = 10^8$K. The results are not very sensitive to these initial temperatures.





While a single supernova cannot fit the soft X-ray data, a multiple supernova model does fit much of the data. This model has some particularly attractive features:

- Long lived solution; we are not unique
- Only weakly dependent on input parameters
- Matches the soft X-ray broad band spectrum and intensity
- Predicted OVI column density matches observations
- Low velocity bubble edge; quiescent solution
- Makes a definite prediction about the OVIII/OVII ratio that can be tested with Chandra.