Observing Between the Shadows in Order to Determine the Halo's O VI Intensity

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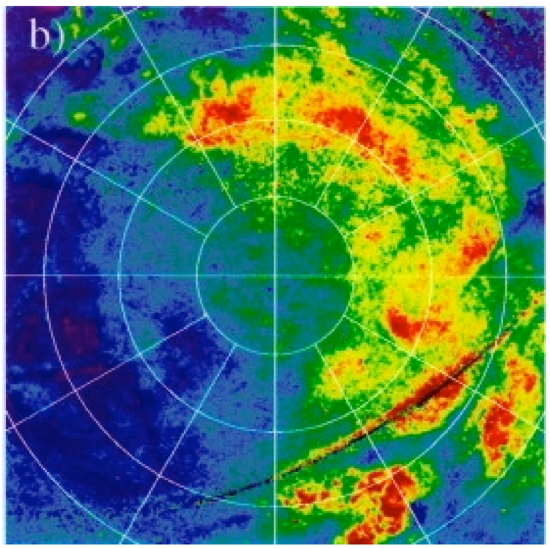
Outline

- Cloud "shadows" separate halo from Local Bubble
- O VI shadowing observations
  - Local Bubble's O VI intensity upper limit
  - Halo's O VI intensity
- Derived physical conditions
- Halo's O VI versus 1/4 keV ratio
  - Temperature power law
  - Cooling rate
  - Implications for maturity of hot gas structure
- Observations of other directions
- Observations of C IV and higher energy X-rays
- Discussion

Text Accompaniment

- This text is being written in order to explain and provide citations for the following overhead slide
  - Observations of emission do not, automatically, tell us the distance to the emitting gas. However, a common way to determine the distance to the gas is to use the "cloud shadowing" technique, as has been done to great effect with X-ray observations. The following is an example.
  - The map on the left is the ROSAT All Sky Survey map of the Southern Galactic hemisphere, from Snowden et al. (1997). It shows the surface brightness of 1/4 keV soft X-ray photons. The red regions are the brightest and the blue/purple regions are the dimmest. The black swath in the lower right quadrant is a region of no data. However, the short line on the right is something else; it is due to attenuation of halo emission by a filament of gas residing between the Sun and the Galactic halo. We can also see the filament in the center image, a map of DIRBE-corrected IRAS 100 micron emission published in Snowden et al. 1997 who obtained the information from Schlegel, Finkbeiner, and Davis (1998) before publication. Thus, the total observed 1/4 keV intensity should be the intensity emitted locally, by the Local Bubble surrounding the solar neighborhood (LB), plus the distant intensity after it has been reduced due to absorption ($I_{obs} = I_{LB} + I_{distant} \times \exp\{-\tau\}$). By fitting this equation to the data, Snowden et al. (1998) determined the 1/4 keV surface brightness of the distant component, which is shown in the right figure.

"Cloud Shadows" Distinguish Local versus Distant Emission Components



Snowden et al. 1997
1/4 keV X-rays (ROSAT)

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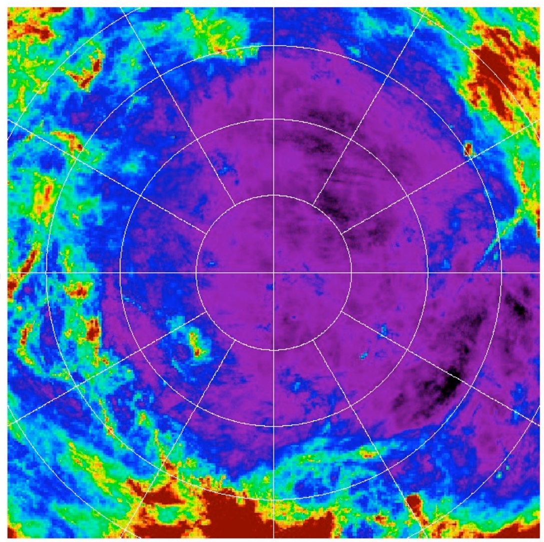
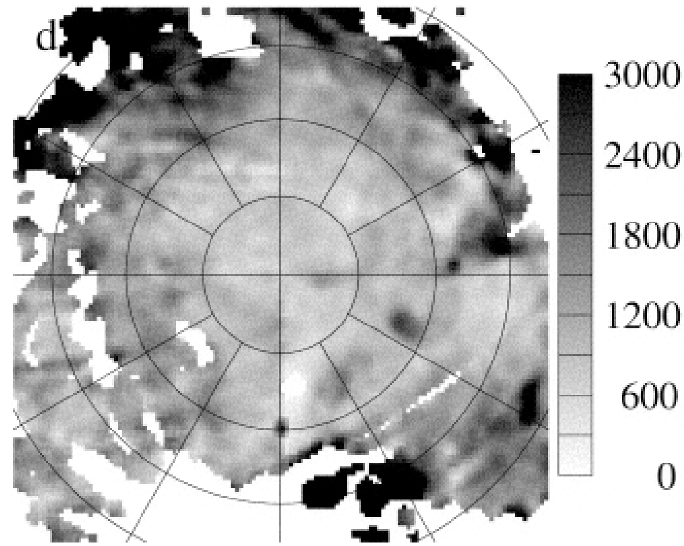


Snowden et al. 1997
DIRBE corrected IRAS



Snowden et al. 1998
Halo 1/4 keV X-rays

Southern sky, X-ray example: $I_{obs} = I_{LB} + I_{distant} \times \exp\{-\tau\}$

Text Accompaniment

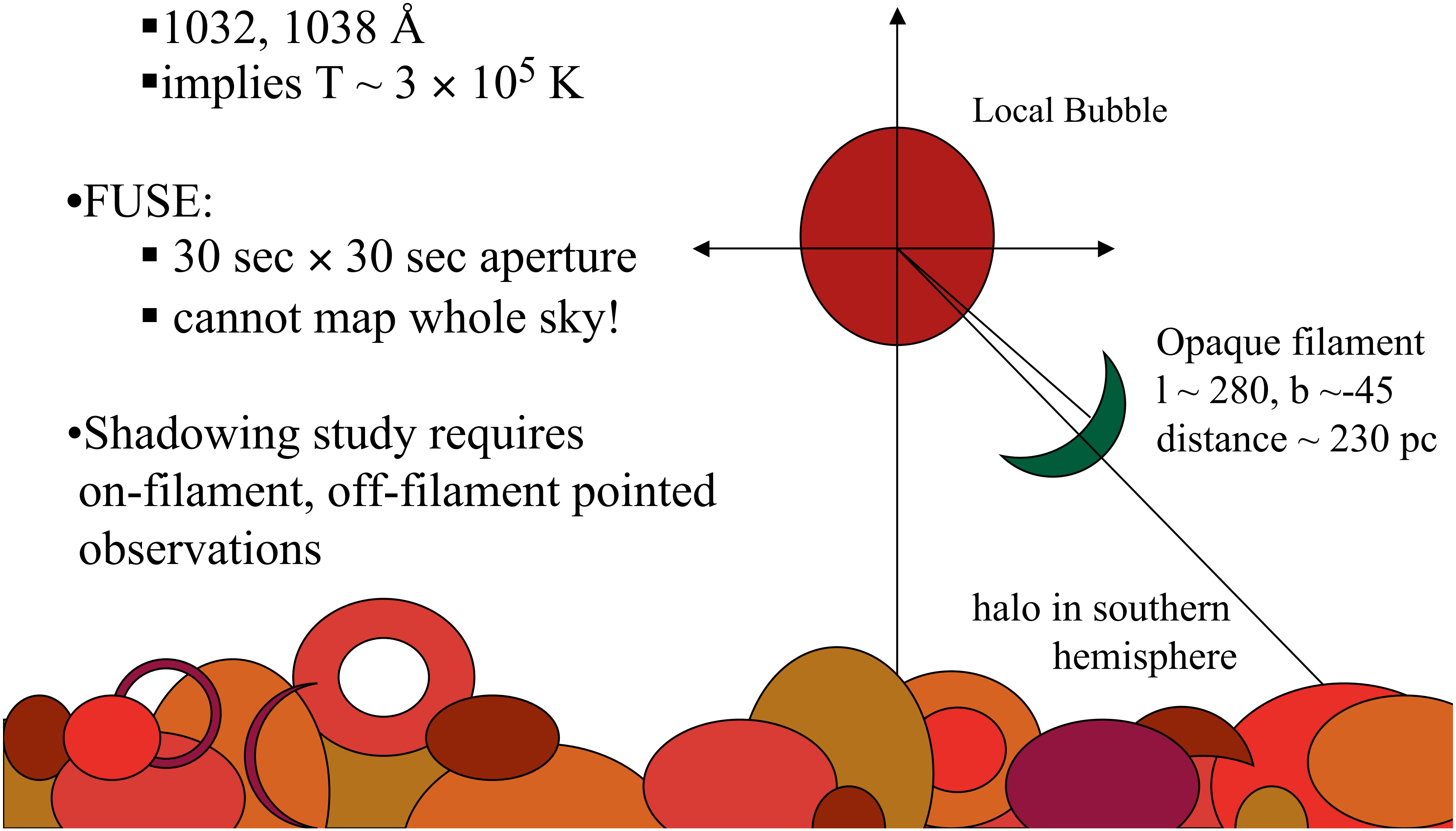
- Here we apply the X-ray shadowing technique to observations of O VI emission.
- O VI has a strong resonance line doublet at 1032 and 1038 Angstroms. If the plasma is in collisional ionizational equilibrium, then the O VI ion is most prevalent when the gas temperature, T, is about 3.2×10^5 K.
- FUSE was used for these observations. However, FUSE's largest aperture is only 30 arcseconds by 30 arcseconds. Clearly, FUSE cannot map the whole sky. So, in order to perform a shadowing analysis, specific on-cloud and off-cloud directions were observed with FUSE.
- The filament shown on the last slide was used as the cloud. It is located in the Southern Galactic hemisphere, approximately 230 parsecs from the Sun, according to Penprase et al. (1998).
- The following cartoon shows the geometry. The axis is centered on the Sun. Around the Sun is the Local Bubble, a hot bubble whose radius is approximately 60 parsecs. The green crescent represents the filament of cool, absorbing gas. The orange and red regions at the bottom of the slide represent hot gas in the halo. The two lines of sight are marked with black lines. One terminates at the filament, because the filament blocks O VI photons emitted beyond it. The other sightline passes by the filament and extends to the southern halo. Note that in studies of the hot gas in the halo (either via O VI photons or soft X-rays), our notion of ”halo” may include space that is only a few hundred parsecs from the Galactic midplane. Current estimates of the hot gas scaleheight are a few to several kiloparsecs.

O VI Emission Observations

- OVI
  - 1032, 1038 Å
  - implies $T \sim 3 \times 10^5$ K

- FUSE:
  - 30 sec × 30 sec aperture
  - cannot map whole sky!

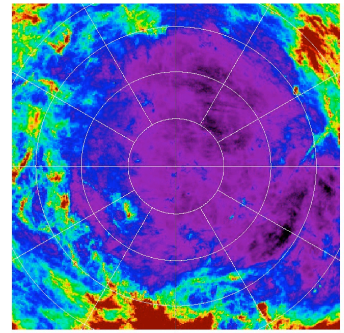
- Shadowing study requires on-filament, off-filament pointed observations

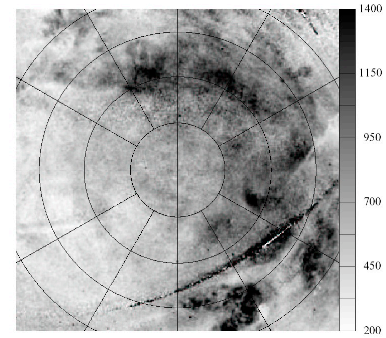


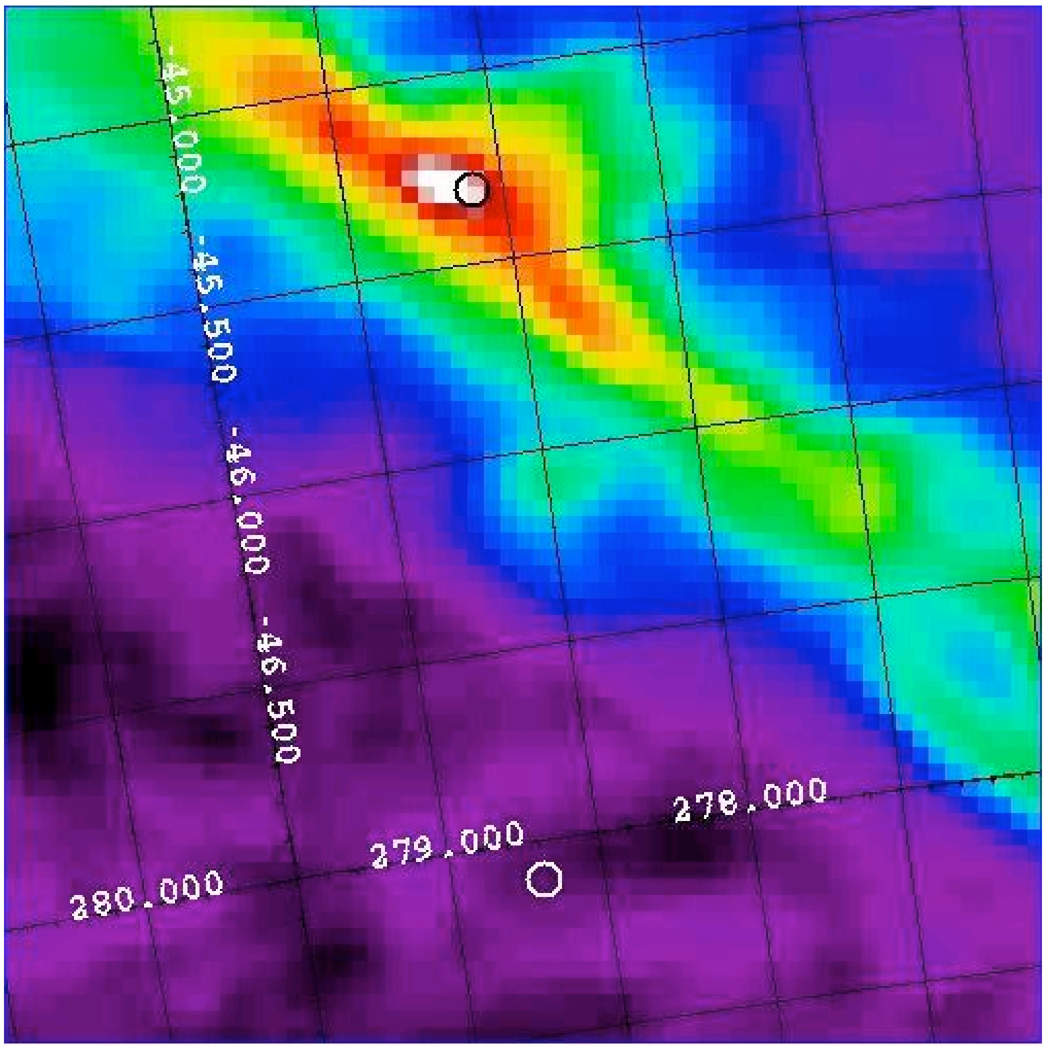
Text accompaniment

- The large figure on the left of the following slide shows the filament region. It is similar to a rotated version of a blow-up of part of the DIRBE-corrected IRAS map shown previously and repeated in the map to the right of the title.
- The two circles on the large figure indicate where FUSE was pointed. The on-filament pointing was toward l = 278.6, b = -45.3. Estimates of the on-filament obscuration range from E(B-V) = 0.17 ± 0.5 magnitudes, from the reported color excesses for nearby stars (Penprase et al. 1998), to a 100 μm level of 7.3 MJy sr^{-1}, from data in Schlegel, Finkbeiner, & Davis (1998). From these values, we (Shelton, Sallmen, & Jenkins, 2007) estimate that the filament blocks 89 (+5,-11)% of 1032, 1038 Å photons. Thus, the FUSE observation toward the filament yields the Local Bubble's intensity, with very little additional contribution from the halo.
- The off filament observation was aimed toward l = 278.7, b = -47.1. We estimated the column density of neutral hydrogen between the Earth and the halo's O VI-rich gas as follows: The total H I column density between the Earth and intergalactic space is ~1 to 2×10^{20} cm^{-2}, based on the 100 μm data and the Leiden-Argentine-Bonn H I survey (Kalberla et al. 2005). However, some of this neutral hydrogen may be above the O VI. Therefore, we used the cavity maps in Lallement et al. (2003) to estimate the minimum H I column density between the Earth and the O VI, finding a minimum of $N_H = 0.5 \times 10^{20}$ cm^{-2}. Henceforth, we use $N_H = 0.5$ to 2.0×10^{20} cm^{-2} as our range of values and $N_H = 1 \times 10^{20}$ cm^{-2} as our nominal value. Given this range in N_H, between 59% and 88% of the OVI photons emitted in regions beyond the absorbing gas are able to pass through the ISM and reach the solar system. Thus, the off-filament FUSE observation yields the Local Bubble's intensity plus a slightly absorbed contribution from the halo.

FUSE Shadowing Observations







- Not unusual part of southern halo
- On-filament:

  l = 278.6, b = -45.3

  E(B-V) = 0.17 ± 0.5 magnitudes

  (Penprase et al. 1998)

  IRAS 100 μm => 7.3 MJy sr^{-1}

  (Schlegel et al 1998)

  Filament blocks 89 (+5,-11)%

  of 1032, 1038 Å photons

- Off-filament:

  l = 278.7, b = -47.1

  $N_H = 0.5$ to 2.0×10^{20} cm^{-2}

  (Lallement et al. 2003, Kalberla et al. 2005, Schlegel et al. 1998)

  Transmits 59% to 88%

  of 1032, 1038 Å photons

Text accompaniment

- The following plots show the FUSE spectra for the on-filament observation in Shelton (2003). The data in the top plot was taken during satellite-night and so contains weaker airglow emission lines and less noise than the data in the bottom plot. The data in the bottom plot is a combination of the satellite-night data and the satellite-day data and so contains strong airglow lines (for example, notice the strong emission line at about 1039 Å).
- Aside from the airglow lines, the spectra is composed of noise. The locations of the O VI doublet's rest wavelengths are marked by obelisks. In both plots, no emission is seen at the O VI rest wavelengths. The tightest upper limit is that for the day+night data on the 1032 Å line. From it, and an expected 1.5 to 1 ratio between the doublet intensity and that of the 1032 Å line, I have estimated the upper limit on O VI doublet emission from the Local Bubble to be $I_{OVI(1\sigma)}$ = 30 (+340,-30) ph/s/cm^2/sr.
- Note that this error bar is for a 1σ statistical uncertainty (random error). It does not include systematic error. This form of reportage, therefore, differs from the reportage in the original paper, Shelton (2003), which listed 2σ uncertainties and included the systematic uncertainties.

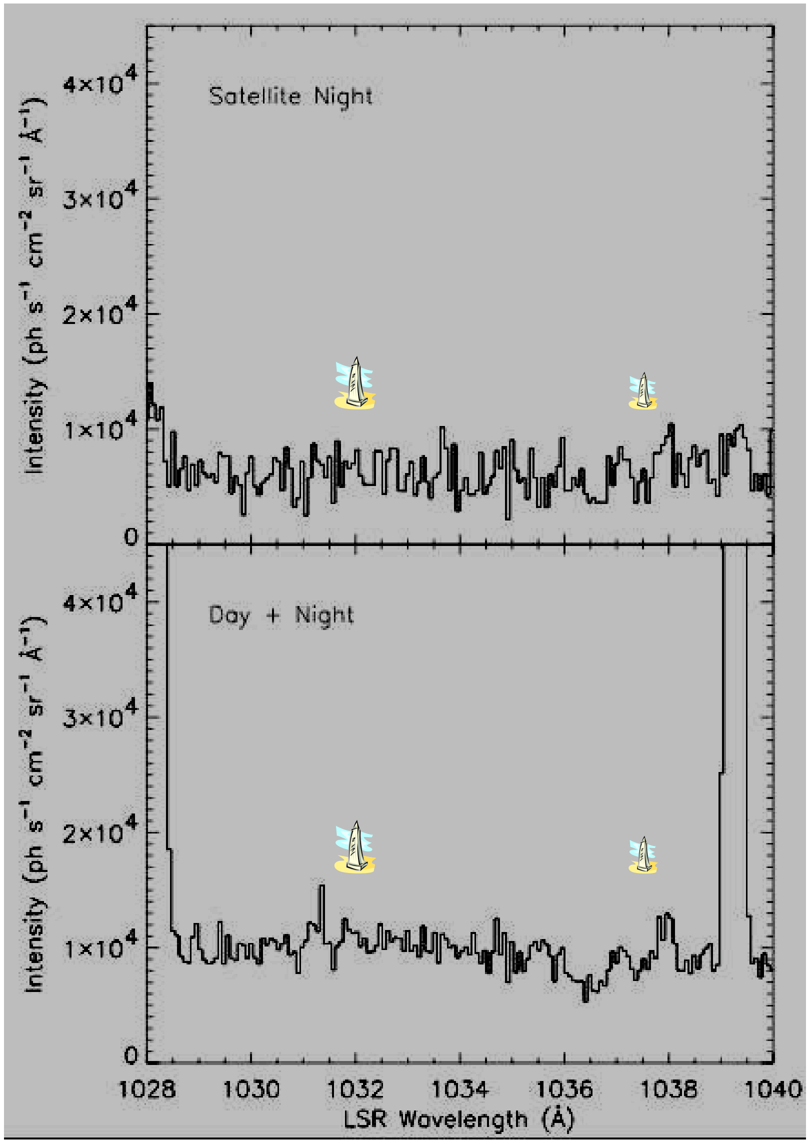
On-Filament Observation

- FUSE shadowing observation ➡ Local Bubble intensity
- Tightest 1σ upper limit on doublet:

  $I_{OVI(1\sigma)}$ = 30 (+340,-30) ph/s/cm^2/sr

  – Note: Tightly constrains Local Bubble and evaporating clouds models

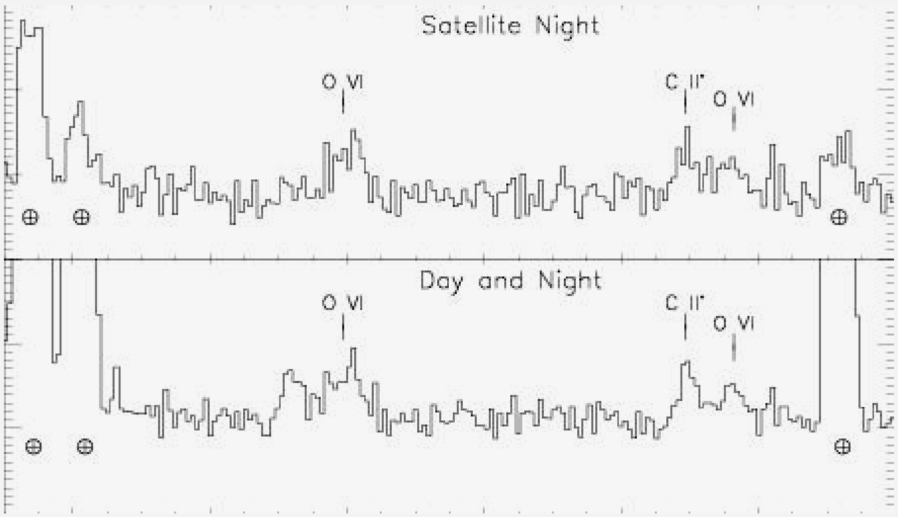
  – Ref: Shelton 2003



Text Accompaniments

- In the following slide, I show the spectra for the off-filament observation. As with the previous slide, the plots of satellite-night and day+night spectra are shown. Unlike in the previous slide, we can now see O VI 1032 Å and 1038 Å emission lines in both plots. They are labeled. We can also see cosmic C II* emission (around 1037 Å). In the lower plot, a weak second-order airglow emission feature appears around 1031 Å, as well.
- These spectra and the following measurements are from Shelton, Sallmen & Jenkins (2007).
- We used 2 methods to measure the emission lines. (These methods are described in Shelton, Sallmen & Jenkins). As you can see from the table, for both the 1032 and the 1038 Å lines, one of the 4 measurements was an outlier. Ignoring these outliers, we averaged the other 3 measurements in order to determine the intensity for the line. We then summed the intensities in the 1032 and 1038 Å lines to yield the doublet intensity, $I_{doublet}$ = 4710 ± 570 ph/s/cm^2/sr, and we subtracted the Local Bubble contribution to find the halo's intensity. However, the true halo intensity is brighter than that observed, due to absorption by intervening material. Given our range in expected N_H, we find the intrinsic halo intensity to be: I_{halo} = 5350 (+650,-750) to 7960 (+970,-1120) ph/s/cm^2/sr.

Off-filament Observation (Local Bubble + absorbed Halo)

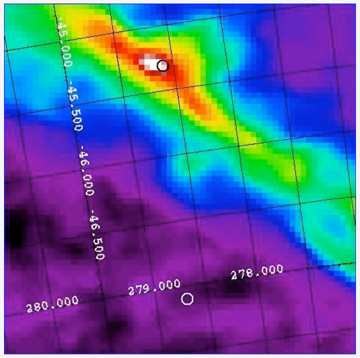


- Average 3 best measurements:
  $I_{1032} = 3190 \pm 450$ ph/s/cm^2/sr
  $I_{1038} = 1520 \pm 350$ ph/s/cm^2/sr
  $\therefore I_{doublet} = 4710 \pm 570$ ph/s/cm^2/sr
- LB subtracted and de-absorbed:
  $I_{halo} = 5350$ (+650,-750) to 7960 (+970,-1120) ph/s/cm^2/sr

Observed Intensities and 1 σ Statistical Uncertainties

	Night Only Method #1 (ph s^{-1} cm^{-2} sr^{-1})	Night Only Method #2 (ph s^{-1} cm^{-2} sr^{-1})	Day+Night Method #1 (ph s^{-1} cm^{-2} sr^{-1})	Day+Night Method #2 (ph s^{-1} cm^{-2} sr^{-1})
O VI 1032 Å	3270 ± 460	3150 ± 540	3150 ± 350	3680 ± 420
O VI 1038 Å	1440 ± 380	2600 ± 630	1490 ± 280	1620 ± 380
C II* 1037 Å	1550 ± 330	1550 ± 400	1700 ± 250	1910 ± 300
1031 Å feature	–	–	1770 ± 260	1770 ± 270

Shelton, Sallmen & Jenkins, 2007



Text Accompaniments

- Next, we turn our attention to the physical conditions in the hot, O VI-rich gas in the halo. We (Shelton, Sallmen & Jenkins, 2007) calculate the electron density in the gas from the doublet intensity and the column density (derived from observations listed in Savage et al. 2003 and reduced by the Local Bubble's O VI column density found from values in Savage & Lehner, 2006), and using the equation in Shull & Slavin (1994). See the next slide for the results.
- Once the electron density is found, the thermal pressure can easily be calculated if we assume that the plasma temperature is approximately 3.2×10^5 K.
- We can also calculate the pathlength of the O VI-rich gas in the halo. Technically, this is a lower limit, because the conversion between the density of O VI ions and the density of oxygen atoms is an upper limit.
- In addition, we have calculated the lower limit on the cooling time necessary. This is the time required to cool if the O VI lines are the only radiator for the O VI-rich gas.

Physical Parameters of the Halo Gas

- $\langle n_e \rangle = (4\pi\ I_{doublet}) / (\langle \sigma \upsilon \rangle N_{OVI})$
- $\Delta\ell = N_{OVI} / n_{OVI} = N_{OVI} / [n_e\ (H/e)\ (O/H)_{\odot}\ f_{OVI}(T_{max})]$

- Take N_{OVI} from average of nearby sight lines (Savage et al. 2003), subtract Local Bubble (data from Savage & Lehner, 2006):

  $N_{OVI} = 2.09 \pm 0.84 \times 10^{14}$ cm^{-2} for halo

- If $N_H = 0.5 \times 10^{20}$ cm^{-2}, then

  $n_e = 0.011 \pm 0.005$ cm^{-3},

  $P_{th}/k = 6700(+2800,-2900)$ K cm^{-3}

  $\Delta\ell = 70 \pm 57$ pc

  Tcool $< 7.4 \pm 3.1$ Myr

- If $N_H = 2 \times 10^{20}$ cm^{-2}, then

  $n_e = 0.016 \pm 0.007$ cm^{-3},

  $P_{th}/k = 10{,}000(+4200,-4300)$

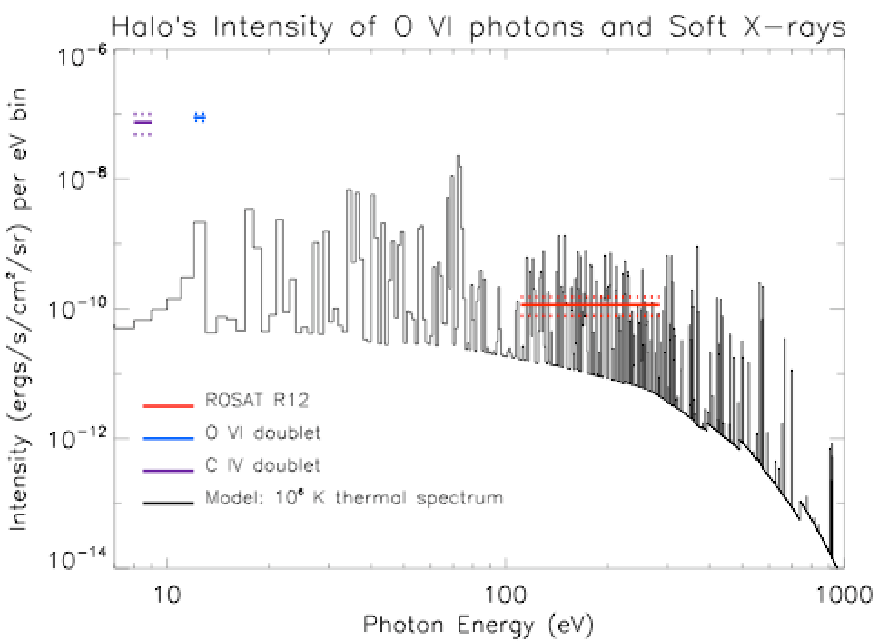
  $\Delta\ell = 47 \pm 38$ pc

  Tcool $< 4.9 \pm 2.1$ Myr

Text Accompaniments

- Here we compare the O VI intensity with the 1/4 keV soft X-ray intensity:
- We used the shadowing technique to estimate the halo's 1/4 keV surface brightness from the ROSAT All Sky Survey data (Snowden et al. 2007) for the same on-filament and off-filament directions used for the FUSE observations. We also subtracted the expected extragalactic contribution and accounted for the interstellar absorption so as to determine the halo's intrinsic brightness.
- Although the ROSAT 1/4 keV band is far wider (~110 to 284 eV) than the O VI emission lines, they radiate less power. (If $N_H = 0.5 \times 10^{20}$ cm^{-2}, then the O VI is 4.7 times as bright as the 1/4 keV band, and if $N_H = 2 \times 10^{20}$ cm^{-2}, then the O VI is 1.1 times as bright as the 1/4 keV band.)
- To express the point, the figure shows the intensity per eV bin (thus the O VI lines are lumped into a single eV bin) for these spectral regions and for the C IV emission recorded by SPEAR (J. Kregenow, personal communication, not LB subtracted). For this figure, we have not de-absorped the intensities.
- Note also that the O VI emission is brighter than is expected from a thermal plasma that is capable of producing the 1/4 keV emission. The spectrum for such a plasma is also plotted on the figure.

O VI Versus 1/4 keV X-rays



Not de-absorbed
C IV from SPEAR,
J. Kregenow communication

- ROSAT 1/4 keV shadowing

  (1322 vs 534 × 10^{-6} c/s/arcmin^2)

- Halo emits more energy in O VI 1032 and 1038 Å photons than in entire ROSAT 1/4 keV band:

  If $N_H = 0.5 \times 10^{20}$ cm^{-2}
  O VI is 4.7 times as bright
  If $N_H = 2 \times 10^{20}$ cm^{-2}
  O VI is 1.1 times as bright

- O VI is brighter than expected from thermal plasma at T = 10^6 K

Text Accompaniments

- From the ratio of O VI intensity to 1/4 keV intensity and the assumption of pressure balance, we can estimate the relative volumes of ~3.2×10^5 K and 1×10^6 K gas in the halo. Furthermore, if we assume a functional form for the volume occupation vs temperature function and bring in the O VI column density and intensity, we can estimate the volume occupied by gas of a given (high) temperature. My collaborator, Ed Jenkins, developed the following technique for doing so.
- Assume that the volume occupation of hot gas follows the functional form: $dl = B\, T^{\beta}\, d(\ln T)$, below T_{cut}. Use the halo's O VI column density and intensity, and the 1/4 keV and 1.5 keV surface brightnesses as constrains to find B and β. The results are shown on the following slide.
- Imagine that the hot gas in the halo were re-arranged so that the $T = 10^5$ K gas was nearest to an imaginary starting point and progressively hotter gas was progressively further away. The plot on the following slide indicates the distances to gas of temperatures between 10^5 and 10^6 K. The plot also indicates the volume density of O VI contained in the gas as a function of temperature. As expected, the curve peaks near 3.2×10^5 K. The majority of the O VI resides within a pathlength of ~100 pc, backing up the simpler estimates made earlier. These results are presented in Shelton, Sallmen & Jenkins (2007).

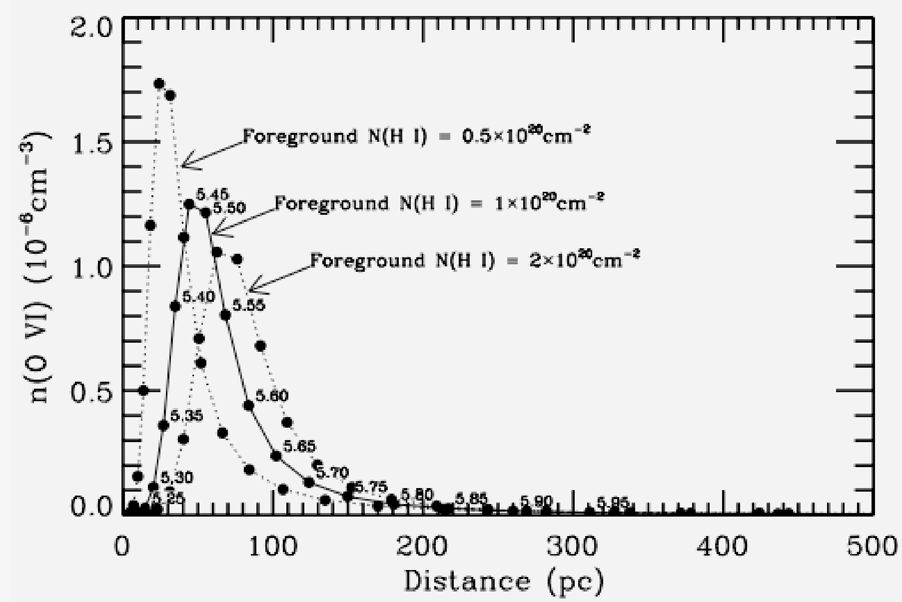
Volume Distribution Function of Temperature

- Assume the volume occupation of hot gas follows power law form:
- Constrain with I_{OVI}, N_{OVI}, ROSAT 1/4 keV (absorbed halo $= 732 \pm 142 \times 10^{-6}$ counts s^{-1} $arcmin^{-2}$) and assumption of pressure balance
- $dl \propto T^{(1.5 \pm 0.6)}\, d(\ln T)$
  - For $N_H = 0.5 \times 10^{20}\ cm^{-2}$ case:

    $dl = 10^{(-4.25 \pm 0.37)}\, T^{(1.15 \pm 0.20)}\, d(\ln T)$

    units $= K^{-\beta}$ pc
  - For $N_H = 2 \times 10^{20}\ cm^{-2}$ case:

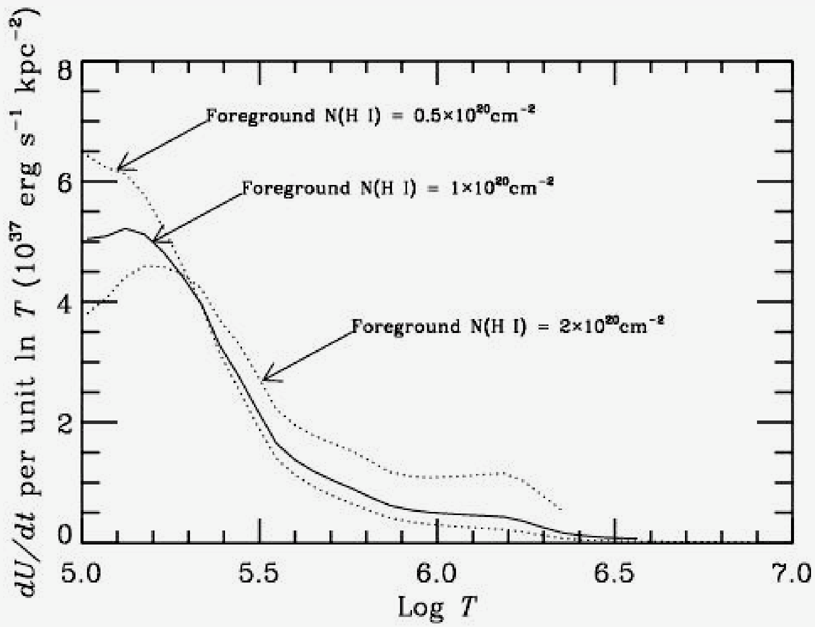
    $dl = 10^{(-8.92 \pm 0.37)}\, T^{(1.95 \pm 0.17)}\, d(\ln T)$



Text Accompaniments

- Using the temperature distribution function on the last slide and assuming that our off-filament line of sight is typical, we have calculated the rate of radiative cooling from the hot gas ($T = 10^5$ K to $\sim 10^{6.4}$ K) in the halo on both sides of the disk: ($\sim 6 \times 10^{38}$ ergs/s/kpc^2).
- This is an enormous rate. In comparison, the energy injected at the Sun's galacto-centric radius by supernova explosions and pre-supernova winds in the disk and halo is about 7.7 to 8.1×10^{38} ergs/s/kpc^2. Thus, the hot gas radiation rate is equivalent to about 70% of the power injection rate of SN and pre-SN winds. Somehow an enormous amount of energy is finding its way into the halo (if our line of sight is typical and the power law valid).

Temperature Distribution Function Implies Large Radiative Cooling Rate



Radiative cooling rate by hot gas

(10^5 K < T < $10^{6.5}$ K, both sides of Galactic plane):

$\sim 6 \times 10^{38}$ ergs/s/kpc^2

For $N_H = 0.5 \times 10^{20}$ cm^{-2},
rate = 4.7 to 6.2 × 10^{38} ergs/s/kpc^2
For $N_H = 2 \times 10^{20}$ cm^{-2},
rate = 5.2 to 6.9 × 10^{38} ergs/s/kpc^2

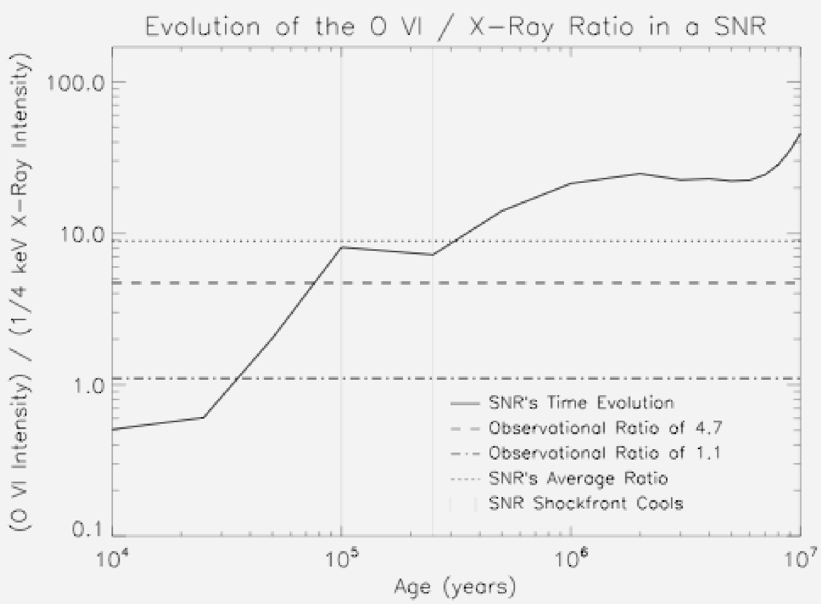
Hot halo gas radiates most of energy injected by SN + pre-SN winds:

(SN + pre-SN wind energy input = 7.7 to 8.1 × 10^{38} ergs/s/kpc^2)

Text Accompaniments

- Another way to analyze the O VI versus 1/4 keV ratio is to assume that both signals come from a single structure, such as a hot bubble blown by a supernova explosion, a plume of hot gas vented in a fountain, or the hot region resulting from a high velocity cloud impact. In such a case, we can use the O VI to 1/4 keV ratio to estimate the degree of maturity of the hot gas structure.
- Here, we consider the hot bubble blown by a supernova explosion. When the supernova remnant bubble is young, it contains both X-ray emissive gas and O VI-rich gas. As it ages, the gas recombines and cools, so the highest ratio of O VI to 1/4 keV emission is at the end of the bubble's life when few X-ray line emitting ions remain.
- The figure on the following slide shows the predicted O VI to 1/4 keV intensity ratio as a function of time. (The modeled SNR is assumed to reside in the thick disk, thus the ambient density is low, 0.01 cm^{-3}, and the remnant is long-lived.) The observationally derived ratio crosses the predicted ratio when the remnant is between 40,000 and 70,000 years old. Although this is before the remnant has formed a cool shell, the remnant is somewhat mature and its plasma has begun to approach collisional ionizational equilibrium by this time.

Rough Estimate of Maturity of the Hot Gas



Assume: previous energetic event shock-heated gas

SNR = prototype

- Initially, more X-ray bright than O VI bright
- Later, X-rays wane faster than O VI

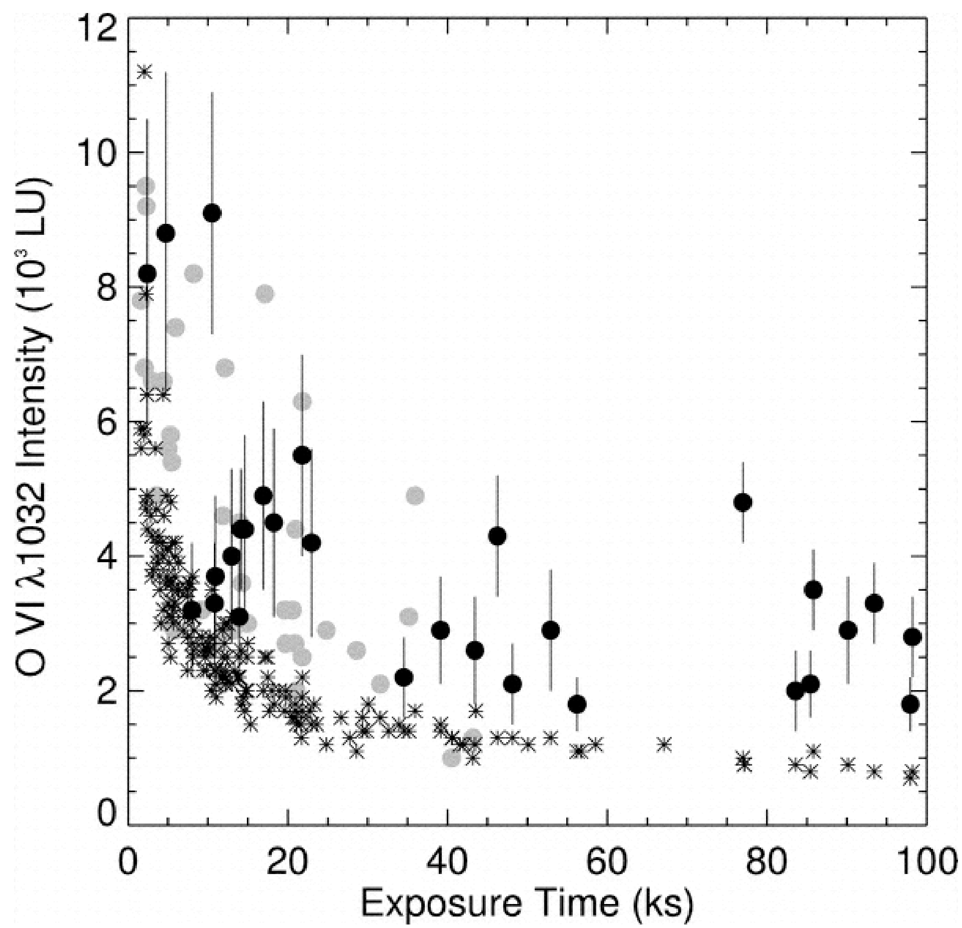
Predicted O VI / 1/4 keV matches observed ratio when SNR in "midlife"

Text Accompaniments

- It is important to know whether or not the chosen off-filament line of sight is typical. This is especially important for the O VI measurement, because the $T = 1$ to 5×10^5 K portion of our temperature distribution function is responsible for much of the predicted cooling rate.
- Here, we compare with the catalog of O VI intensity measurements published by Dixon, Sankrit, and Otte (2006). The following figure shows their observed and upper limit 1032 Å intensities (not the doublet intensities) as a function of observation time. Let us confine ourselves to their observations lasting 40 ksec or longer. Also, let us only consider observations of $|b| > 30^o$ and $|v| < 100$ km sec^{-1}. Our off-filament 1032 Å intensity is near the center of the pack of such a subset.

O VI Observation Consistent with Other Directions

- Dixon, Sankrit & Otte, 2006 FUSE survey
- 186 archived sight lines
  - Examined 1032 Å signal
  - 3σ detections ●
  - 2σ detections ●
  - upper limits ✳
- Our off-filament obs is near median of survey intensities:
  - Compared with sight lines with
    |b| > 30°,
    exposure > 40 ksec, and
    |v| < 100 km sec^{-1}



Text Accompaniments

- The O VI and ROSAT 1/4 keV observations best examined ~3×10^5 K and 1×10^6 K plasma. The neighboring temperature ranges are probed by C IV ($T \sim 1 \times 10^5$ K) and XMM soft X-rays ($T \sim 10^6$ K and higher)
- SPEAR (PI = J. Edelstein) has made C IV observations near the off-filament direction. The nearest observation is toward l = 279.6, b = -47.2, where SPEAR recorded an intensity of $I_{CIV} = 5792.0 \pm 1997$ ph/s/cm^2/sr (J. Kregenow, personal communication). This is consistent with our power law.
- XMM has observed the same on-filament and off-filament directions as FUSE. Henley, Shelton & Kuntz (2007) and Lei et al. (in preparation) have analyzed these observations. Their analysis techniques account for the Local Bubble emission, the absorbed halo emission, and the absorbed extragalactic power law. They find less emission from ~2 to 3×10^6 K than would be expected from the O VI - 1/4 keV derived temperature distribution function and they fit the XMM spectra with a more steeply decreasing emission measure function. This means that the power-law form of the temperature distribution function described earlier must have a break in it somewhere near 10^6 K. This finding does not significantly effect the predicted radiative cooling rate presented several slides back, because the hotter gas contributes little to the total cooling rate.

Extending the Spectrum: SPEAR & XMM Observations

- SPEAR: l = 279.6, b = -47.2 (near our pointings)
  - I_{CIV} = 5792.0 ± 1997 ph/s/cm^2/sr
  - Consistent with power law
- XMM: Same on-filament and off-filament directions
  - Model:
    - Local Bubble + Absorbed {Halo + Extragalactic}
    - Simultaneously fit spectra, absorption N_H depends on direction
  - Results:
    - See less halo 0.4 to 1.0 keV intensity than expected ∴ Break in power law distribution between the (brighter) O VI to 1/4 keV regime and the (dimmer) O VII regime

Discussion

- We have examined OVI in the halo in the southern hemisphere (b ~-46^o)
  - n_e = 0.006 to 0.023 cm^{-3}, p_{th}/k = 4000 to 14,000 K cm^{-3}
  - Obs fit power law distribution: $dl \propto T^{(1.5 \pm 0.6)}\, d(\ln T)$
  - High radiative cooling rate of T > 10^5 K gas
  - O VI to 1/4 keV ratio is sign of middle-aged structure
- C IV data consistent, XMM spectra dimmer
- Thoughts for the future:
  - Variation across the sky?
  - Causal link with known structures?