Global Models of the Galactic Interstellar Medium: Comparison to X-Ray and H I Observations

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ABSTRACT

In a previous paper, we calculated numerical hydrodynamic models of the interstellar medium in the Galaxy, which suggested that hot gas ($T \geq 3 \times 10^5$ K) has a filling factor near 50% in the midplane, and that it is separated by cooler material [Rosen & Bregman 1995]. Here we extend the work to examine the X-ray emission characteristics of the best model and calculate a variety of observable measures for comparison with the observed soft X-ray background. For five observer locations in the disk (three hot bubbles, a cooler bubble, and a neutral gas region), we calculate the X-ray intensities, spectra, and hardness ratios in 0.16 – 0.28 keV and 0.53 – 0.87 keV bands as Galactic latitude and cool gas column are varied. We compare these to strip scans of observational data, $N_{\text{HI}}$ from Dickey & Lockman 1990, and C band and M I band X-ray data from the Wisconsin surveys [McCammon et al. 1983].

The calculated neutral hydrogen column density distribution has a broad range and a median value that is typically 2.5-6 times smaller than the mean value (seen from a location in the disk or perpendicular to the disk). This difference between the mean and median $N_{\text{HI}}$ offers a natural explanation for the observed difference (a factor of three) between the average $N_{\text{HI}}$ at the solar circle and the local value deduced from high-latitude observations. The observed distribution of $N_{\text{HI}}$ is similar to that seen from one of the simulated bubbles, with the important exception that the minimum hydrogen column in the model is too low. The low minimum hydrogen column is a common result of the models and indicates that neutral gas is too easily compressed into small structures.

The models suggest that the X-ray emission in the 0.16 – 0.28 keV band is dominated by hot gas within 0.1 – 0.5 kpc while in the 0.53 – 0.87 keV band, nearly all emission originates within 2 kpc of the observer, and often much closer. The model X-ray emission generally hardens toward the plane, for observers in bubbles. Also, there are clear examples of anticorrelations between H I and X-ray emission as well as correlations between H I and X-rays, which is caused by an increased emission measure as a shock enters a cool gas region. Statistically, anticorrelations are slightly more common than correlations. X-ray spectra are calculated from the models and these reveal that for observations to have strong diagnostic power in probing the hot ISM, a spectral resolution of $E/\Delta E > 30$ is required.

The X-ray observations reveal shortcomings in the models in that the angular distributions of the model X-ray intensities and the hardness ratios vary far more than the observations in

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either energy band. Also, the model X-ray intensities are typically fainter than observed. Some of these shortcomings may have been alleviated had we chosen a more uniform and denser hot bubble, but we suggest that this problem, as well as the low H I values, might be solved by including magnetic fields in future simulations.

Subject headings: Hydrodynamics — ISM: Structure — X-Rays: ISM

1. Introduction

The interstellar medium of the Galaxy is very diverse, with gas components of temperatures ranging from $10^{-10}$ K in close spatial proximity. Each component is important either from mass considerations, where the cold molecular gas and neutral atomic gas account for most of the gaseous mass, or from volumetric considerations, where the ionized phases may occupy most of the volume. Furthermore, the ISM in the Milky Way appears to be typical of other spiral galaxies, where these various gaseous components are commonly observed.

There is general understanding that the structure of our ISM is descended from the interplay between star formation, stellar evolution (including the essential heating events) and the gaseous disk in which they are embedded. Analytical models for the global ISM have focused on issues of pressures and filling factors, usually making assumptions about the geometry and structure of the gaseous components (e.g., neutral gas lies in clouds; SNR expand into a uniform medium). Such assumptions can be avoided in numerical models, but these calculations are challenging even with modern computers, so it is often necessary to examine only a piece of the problem (e.g., magnetically expanding superbubbles) or to make other concessions when considering the global problem.

We and collaborators have taken the path of developing global numerical models for the interstellar medium on scales larger than the biggest individual elements (superbubbles) so that the full range of interstellar phenomena can develop with a minimum of assumptions. In this model, the stars and the gas are represented as separate fluids that can interact. Cool gas forms into stars at a rate proportional to the gas density, and evolving stars return gas to the ISM. The stars heat the gas through a combination of stellar winds and supernovae, with the latter being the more important of the two heating mechanisms. The gas evolves according to the Euler equations, modified by these source and sink terms, as well as by optically thin radiative cooling.

The early two-dimensional calculations with this model were for the midplane of a galaxy (no gravity), used a first-order accurate numerical code (the “beam scheme”: Chiang & Prendergast 1985; Chiang & Bregman 1988), and revealed a common structure for the gas, with cold dense filaments (probably sheets in three dimensions) frequently surrounding bubbles of warm dilute gas. Subsequently the model was improved by using a second-order accurate numerical code (“Zeus-2D”: Stone & Norman 1992; Rosen, Bregman, & Norman 1993; and Rosen & Bregman 1995, hereafter RB) and two-dimensional calculations were performed where one dimension is perpendicular to the plane. The models given in RB are the most realistic to date and they include supernova heating as well as stellar wind heating. These models demonstrate that by matching the models to certain basic observations, such as the scale heights of the gaseous components and the pressures, it is possible to determine the volume filling factors and topology of these components.

We are encouraged by the results of these models and their ability to reproduce certain basic observations. However, we are aware that the model presently lacks certain important physics (most
notably, a magnetic field and a third independent dimension) and that there may be other observables that could provide much greater diagnostic power in identifying the model most representative of the Milky Way. In this paper, we compare our most successful model (from RB) to the spatial distributions of 21 cm emission from H I and of the soft X-ray background from the Galaxy. These observables prove to be extremely powerful diagnostics in identifying the weakness and strengths of the calculations and point the way toward future development.

In this paper, we will discuss the hydrodynamical model of RB in a bit more depth in §2, compare the distribution of $N_{\text{H}I}$ from a variety of positions within the model with observational data in §3, and compare the X-ray intensities from the model with observations in §4. Our results are summarized and a plan for our future work in regard to diffuse Galactic X-ray emission is discussed in §5.

2. Our Hydrodynamical Simulation

All of the simulations in RB were run with a two-dimensional version of the Zeus hydrodynamical code, modified to allow for the evolution of two interacting cospatial fluids. The two cospatial fluids represent the stars and gas in the interstellar medium, with the stellar “fluid” having characteristics of a mean Population I star. The star formation rate and mass loss rate are equal, and they are set so that their inverse gives an effective stellar lifetime of $10^8$ yr. One of the dimensions represents the vertical axis of the Galaxy, with a time-invariant external potential imposed along this axis, which we will designate as $z$. The other dimension is in the plane, although it is neither radial nor azimuthal, since the simulations in RB did not include rotational effects, and we designate this axis as $x$. The simulation was run for 300 Myr, and the image chosen was at a program time of 215 Myr. The grid used for the simulation is a $200 \times 400$ zone grid, and is linearly scaled with 10 pc zones in both directions in the inner 200 rows (a $2 \times 2$ kpc region). The outer 100 rows on both the top and bottom of the grid are 2 kpc across, but extend from $1 - 15$ kpc with the zone size increasing geometrically along $z$ (see Figure 1a). Also, the boundary conditions are periodic along the vertical edges of the grid (as shown in Figure 1), and allow outflow along the horizontal edges.

In order to simplify a complex problem in the simulations of RB, the ionization of the gas fluid was incorporated in only two aspects of the hydrodynamical code. Ionization effects were only crudely taken into account in the cooling function, which was a series of power laws that match fully ionized gas above 8000 K and gas that became less ionized with lower temperature. The second place where an ionization was assumed for the gas was in the constant mean molecular weight (= 0.6) in the calculation of gas temperatures.

Of the six simulations in RB, which varied in the rate and form of energy injection, we analyze an image from the simulation that seems most similar to the Galaxy, i.e. one that has a Galactic energy injection rate and that includes supernovae. This simulation naturally recreates a multi-phase medium with cold, dense filaments ($T \sim 300$ K, $n \sim 10$ cm$^{-3}$) surrounding bubbles of hot gas ($T \sim 10^6$ K, $n \sim 0.001$ cm$^{-3}$ in the midplane), which is similar to the topology in Figure 9a of Burrows et al. (1993) of the Eridanus region. Also, this simulation reproduces quite well the scale heights and central densities of a three phase medium with multiple components in each phase.

In this paper, we will define cold gas in the simulations as gas with $T$, the gas temperature, < 4000 K, warm gas with 4000 K < $T$ < and 300,000 K, cool gas with $T$ < 300,000 K (both cold and warm gas), and hot gas with $T$ > 300,000 K. The upper temperature limit for the cold gas is consistent with observations of the warm neutral medium reported in Verschuur & Magnani (1994), therefore cold gas in the simulations
of RB should be neutral hydrogen.

Previously, we compared the results of the simulations to the observed scale heights and pressures of the interstellar medium and met with some success. However, the observations contain considerably more information, such as the range of intensities as seen from the Sun and the angular distribution of these intensities. Here we calculate the angular distribution of H I and X-ray intensities from five different locations in the simulations: three hot bubbles, a large region filled with both warm and hot gas, and a dense neutral region. The temperature distributions of the five regions are shown in Figure 1. Some properties of the regions are characterized in Table 1, which gives the zone locations \((x, z)\), height above the midplane, mean density, mean temperature, and the median pressure for the five regions shown in Figure 1c.

Bubbles 1 – 3 are dominated locally by hot gas and so should be most similar to the hot bubble around the Sun. These bubbles were chosen as characteristic of the simulations rather than being a close match to our local bubble, so in the comparison that we will make below, we will emphasize generic similarities or differences. The three hot bubbles from the simulation represent a range of temperatures, densities, and heights above the midplane.

The main difference between the three hot bubbles is the average temperature in the bubble, which is larger in Bubbles 2 and 3 than in Bubble 1. Variations in the average temperature in the bubbles are caused by different elapsed times since the most recent supernova in each bubble. Note that Bubble 2 is also farther removed from the midplane \(|z| = 230\ \text{pc}\), as opposed to Bubble 1, which is within 10 pc of the midplane, and Bubble 3 with \(|z| = 60\ \text{pc}\). The median pressures listed in Table 1 for each of the five positions show that the hot bubbles have the highest median pressure, with the cooler gas zones at a median pressure that is half an order of magnitude lower. This is consistent with an observational result (Bowyer et al. 1995) and one result in RB, that the hot gas is overpressured with respect to the rest of the gas.

Sample lines of sight out to a distance of 5 kpc from Position 1 are also shown in Figure 1a. Since only the hot gas contributes to the X-ray intensity (see below), we display only hot gas in Figure 1b. The extents of the “local” bubbles at the first three positions are shown in Figure 1c, where we define local as the extent of each line of sight until it first encounters a cool temperature zone. This definition emphasizes the X-ray brightness in the definition of the bubble’s extent.

3. A Comparison with Galactic H I

There are a variety of 21 cm observations of neutral hydrogen that serve to characterize the large-scale radial and vertical distributions, the pressure, and the angular distribution on the sky. The Galactic H I vertical distribution and pressure were reproduced by Run E in our simulations (above), and here we extend the comparison between model and observational data. Comparisons between the model and the observations are performed for the column density distribution, primarily as a function of Galactic latitude. Aside from examining the H I distribution, we examine the relationship between neutral hydrogen and X-ray emitting gas. In the soft X-ray bands, neutral gas is the dominant absorber of X-rays and there are a number of observations that stress this comparison. The relationship between the H I and X-ray emitting gas is discussed in detail in §4.6.

The H I data (kindly provided by Lockman; see Dickey & Lockman 1990, hereafter DL) have been compiled from many surveys and averaged over \(1^\circ \times 1^\circ\). From these data, we extracted a single strip
that passes through both Galactic Poles, and through 0° latitude at longitudes of 90° and 270°. Two considerations assisted in the choice of this strip: 1) that the simulations of RB did not include rotational effects, and 2) that we wanted to compare our model with a symmetrical distribution of H I in the Galactic disk, i.e. one of equal length through the Galactic disk at both longitudes.

From our model, we calculate a distribution of cold and cool gas as a function of latitude for each of the five positions. There can be only one such distribution per location since the simulation has only two independent coordinates. The column density is calculated from the lower left-hand corner of the zone location (Table 1) and along a line with a constant 1 cm² cross-section. We have computed these column densities for all latitudes with 0′5 separation (720 lines of sight), and thereby generated a simulated scan. For each line of sight, we have calculated the column density to a distance of 5 kpc from the initial position, making use of the periodic boundary conditions employed in the (2 kpc wide) hydrodynamical simulation where necessary. The bending of sample lines of sights, shown in Figure 1a, once out of the central region (rows 100 – 300) is caused by the logarithmic scaling of the vertical size (from a height of 1 kpc 100 rows from the midplane to 15 kpc at the edge of the grid) of zones in these rows. We have not smoothed the variations of any of our strip surveys in angular resolution.

The maxima in the N H I plots always occur near the midplane (b = 0°L or 0°R, see Fig. 2), which results from the line of sight crossing the entire width of the grid 2.5 times through the densest gas. The minima in N H I are usually, although not always, at lines of sight near each pole at b = ± 90°; an exception to this is a minimum in Bubble 1 at b = 30°L.

First, we compare the distribution of column densities between the model and the observations. To do so, we calculated the minimum, low quartile (25%), median, high quartile (75%), maximum, mean, and the fluctuation statistic, \( \delta_i = \sqrt{\langle \sigma^2 \rangle - \langle \sigma \rangle^2} / \langle \sigma \rangle \), in the strip surveys in N H I (see Table 2). The fluctuation statistic, listed in the last column of this table, is a measure of the width of the distribution. In Table 2, we have also included similar statistical quantities for the single strip of data from the DL dataset. The H I statistics for the model data contain many trends, all of which can be explained by a combination of two effects: that smaller values of N H I depend on the local conditions, while the larger values of N H I (specifically the maxima) depend primarily on the height of the position above the midplane (z = 200 zones).

The statistical quantities for lower values of N H I are determined by the local environment; specifically, the minima (column 2), low quartiles (column 3), and medians (column 4) of the three bubbles are all close to each other, while those from Position 4 are the smallest in each column, and those from Position 5 are the largest. Position 4 has the smallest values in these columns because the superbubble at b = +90° has heated the cold gas so that it is completely ionized toward some latitudes in this direction. The positions in the three bubbles of hot gas have intermediate values in columns 2 – 4 of Table 2, and these positions all have \( \log(\text{minimum N}_\text{H I}) \sim 18.5 \) and median values of \( \log N_{\text{H I}} \sim 20.1 \). The largest values of H I minima, low quartiles, and medians are associated with the dense clump of cold gas at Position 5.

The positional variation of the maxima (column 6 of Table 2) and the high quartile (column 5) model data follow different patterns from the variation of the lower statistical quantities. The physical significance of this difference is revealed by comparing column 6 in Table 2 with the height above the midplane, \( |z| \), which is given in column 3 of Table 1. The three positions with \( |z| = 10 \) pc all have roughly the same maxima (log N H I ~ 22.4), and this is caused by low latitude lines of sight that pass through the disk. The smallest maximum N H I occurs at Position 2, which is at a large enough height that the lines of sight that pass through the midplane do so for a shorter path length than sightlines closer to the midplane.

With the exception of some very low N H I in a portion of the sky, the distribution of N H I surrounding
Bubble 3 is similar to the observed Galactic distribution of \( N_{\text{H}} \). The model data from Bubble 3 is most like the data from the DL strip in every column of Table 2 (except for the high quartile in column 5), including the fluctuation statistic. We display the latitude variation of the strip taken from the DL \( N_{\text{H}} \) data with the ones created from each of the five positions in the simulation in Figure 2. In addition, we plot histograms of the six distributions, for each of the 5 positions and the DL strip, in Figure 3. Each of the simulated sets of \( N_{\text{H}} \) within Bubbles 1, 2, and 3 (Figures 2a, 2b, and 2c) has a smaller minimum value than the observations. From Figures 2 and 3 and Table 2, the model distributions from Positions 4 and 5 quite definitely do not fit the observations, because Position 4 has too many low \( N_{\text{H}} \) lines of sight and Position 5 has too few. Of Bubbles 1, 2, and 3, the latitude dependence of \( N_{\text{H}} \) (Figure 2) shows that only Bubble 3 has nearly as many lines of sight with \( N_{\text{H}} \) above the observational strip of data as below it. Also, the histograms in Figures 3a, 3b, and 3c show that Bubble 3 has a distribution that is most similar to the DL data in Figure 3f, although there are enough \( N_{\text{H}} \) sightlines with small values seen from Bubble 3 that it is not a very good match. By comparison, the observed distribution of H I has very few regions of low column density, with the minimum H I column density in the Ursa Major region (log \( N_{\text{H}} = 19.64 \), [Jahoda, Lockman, & McCammon 1990]) and a sharp cutoff below log \( N_{\text{H}} = 20.0 \) (see Figure 4 in DL for the histogram of the entire dataset).

This comparison between observations and simulations leads to an explanation for the observational fact that the H I column above the Sun is about one-third the mean value at the solar circle. This difference in the mean and local columns either is an important clue to the nature of the neutral ISM, or it is an unrepresentative situation that occurred by chance. Our calculations suggest the former. An inspection of mean and median \( N_{\text{H}} \) in the model data reveals that the median is consistently lower than the mean, and for the bubbles of hot gas the ratio of the two is close to the observed value. The ratio of mean to median in columns 4 and 7 of Table 2 is \( 2.5 - 6 \) in each of the positions within bubbles of hot gas. This is similar to the difference between the typical column of neutral hydrogen at high latitudes (\( \sim 1 \times 10^{20} \text{ cm}^{-2} \)) and the half-column through the observationally derived mean distribution of the entire set of \( N_{\text{H}} \) data (from DL, \( \sim 3 \times 10^{20} \text{ cm}^{-2} \)). This result occurs because of the low filling factor of the H I, so only a few H I structures are found along any line of sight through the disk, and some of these structures contain considerable H I mass. Also, this leads to the prediction that for lines of sight through the H I disks of external galaxies, the H I absorption column toward a point source will usually be lower than the H I emission column seen in a large beam (e.g., a beamsize greater than the characteristic structure size of a few hundred pc). This has the implication that in external galaxies the determination of the H I spin temperature will typically be underestimated from standard techniques (e.g., the ratio of 21 cm absorption to emission measures; for the above beamsize situation).

4. A Comparison with the Galactic Soft X-Ray Background

The soft X-ray observations can provide some of the strongest constraints for any model of the ISM, although the use of this data is complicated by the presence of an extragalactic X-ray background and by the absorption effects of cool gas in the Galaxy. Here, we present calculations of the X-ray emission properties of our models which are compared to X-ray observations as well as to the absorbing H I material.
4.1. An Overview of X-Ray Background Observations

The X-ray background is dominated by extragalactic sources at energies above about 1 – 2 keV, but at lower energies, $E < 1$ keV, the X-ray background is a local phenomenon that is caused by hot gas in the Galaxy (reviews by McCammon & Sanders 1990, Fabian & Barcons 1992). The emission in the softest bands (0.1 – 0.5 keV) is dominated by the Local Bubble of hot gas surrounding the Sun, which is 100 pc in size and has a temperature near $1 \times 10^6$ K. The absorption by neutral Galactic gas prevents us from sampling far into the Galaxy at the lowest energies, 0.1 – 0.2 keV, where an optical depth of unity is reached after only $0.2 – 1 \times 10^{20}$ cm$^{-2}$. Because the absorption cross-section decreases quickly with energy (e.g., Morrison & McCammon 1983), an optical depth of unity is reached for a path length in the disk of about 1 kpc at an energy of 0.7 keV and 5 kpc at an energy of 1.5 keV. At these energies, it is possible to observe features beyond our Local Bubble. Consequently, we will examine the X-ray background at two energy bands, near 0.2 keV and 0.7 keV.

Sensitive large-scale surveys of the soft (Galactic) X-ray background were carried out by the Wisconsin X-ray group with sounding rockets (7$^\circ$ resolution; McCammon et al. 1983), from the SAS 3 satellite (0.25 keV map with 4.5$^\circ$ resolution; Marshall and Clark 1984), and with the A2 LED detectors on HEAO 1 (0.12 – 3 keV and 3$^\circ$ resolution; Garmire et al. 1992). These observations showed a structured X-ray sky, with order-of-magnitude variations in the diffuse emission, and brightening in the softest X-ray bands toward the north and south Galactic poles.

The X-ray satellite ROSAT improved the ability to study the X-ray background due to substantially better angular resolution (1$'$), which allowed high sensitivity shadowing experiments to be performed (review by Burrows & Mendenhall 1994). In these shadowing experiments, one observes in the direction of neutral gas clouds (H I) with a known distance that places them beyond the Local Bubble. If all of the soft emission is from the Local Bubble, no shadow is seen, so it was extremely exciting that shadows were seen in some directions (Burrows & Mendenhall 1991), usually along lines of sight out of the plane. In the plane, shadowing by clouds at energies near $1/4$ keV is uncommon. At higher energies (e.g., $3/4$ keV), observations in the plane of the Galaxy commonly reveal shadowing, indicating that most of this emission is from within a few kiloparsecs of the Sun (Burrows & Mendenhall 1994), and Stanford & Caillault (1994) present a model for this distribution (note that at low latitude, the disk blocks the extragalactic contribution to this component).

In a complementary effort, workers have sought to identify individual features or structures, and have found several large bubbles, which are explained as reheated supernova remnants and superbubbles. Some examples are the Cygnus superbubble (Cash et al. 1980), the Monogem Ring (Plucinsky et al. 1994), and the Orion-Eridanus enhancement (Nousek et al. 1982), all nearby objects (few hundred pc) that subtend large angles on the sky (several tens of degrees). The study of the hot ISM at kiloparsec distances requires angular resolution of 0.3 – 1$'$ at 0.5 – 1.5 keV energies, and some programs are being carried out with the ROSAT PSPC All-Sky Survey (Snowden et al. 1994a, hereafter SHJLMS; Snowden et al. 1995a; and Snowden et al. 1995b).

4.2. The X-Ray Observations Used Here

As in the comparison of H I data, we require characteristic measures of intensity as a function of latitude around the sky. For these all-sky X-ray scan data, we use the observations obtained by the Wisconsin group in their C and M$_1$ bands, which have 20% response points defining the bands at 0.16
– 0.284 keV and 0.44 – 0.93, respectively (McCammon et al. 1983). These observations have angular resolutions of 7° (FWHM) in C band and 6.2° in M₁ band, and although that is considerably inferior to ROSAT (effective angular resolution of about 1° in the ROSAT All Sky Survey, due to the need to bin the data to improve photon statistics), the ROSAT data were not publicly available at this writing and their equivalent energy bands are not as cleanly defined (nevertheless, a qualitative comparison to some of the ROSAT observations is made).

The X-ray surface brightness as a function of Galactic latitude was extracted for a strip that passes through the Galactic longitudes of 90° and 270°. There are a few particularly bright portions of the X-ray data due to discrete sources and they have been removed (3 of 360 points in the C band strip and 11 of 360 points in the M₁ band strip).

4.3. The X-Ray Model Intensities

For each of the five positions from which we generated the neutral hydrogen strip scans, we have created X-ray intensity strip surveys (with the same angular separation between adjacent lines of sight, 0°5) in two soft X-ray bands: a band between 0.155 – 0.284 keV, which is similar to the Wisconsin C band (0.16 – 0.284 keV; McCammon et al. 1983) and also the ROSAT R2 band (the 10% points are 0.14 – 0.284 keV; Snowden et al. 1994b), and one between 0.532 – 0.873 keV, which is similar to but narrower than both the Wisconsin M₁ band (0.44 – 0.93 keV) and the ROSAT R4 band (0.44 – 1.01 keV). Our energy bands do not include an instrumental response as a function of energy, which is different for each instrument. The energy bands that we chose are two of the six energy bands for which Raymond, Cox, & Smith (1976) have discussed the cooling coefficient, Λ, as a function of temperature. We will refer to each model band by its mean (0.22 keV and 0.70 keV), and these values will always indicate simulated data.

The computation of the X-ray intensity (I) is based on a combination of the program outlined in §3 and on an updated version of the X-ray emission code described in Raymond & Smith (1977). The cosmic abundances used are from Allen (1973) (in the log relative to hydrogen = 12.00): He, 10.93; C, 8.52; N, 7.96; O, 8.82; Ne, 7.92; Mg, 7.42; Si, 7.52; S, 7.20; Ar, 6.90; Ca, 6.30; Fe, 7.60; and Ni, 6.30. This code was used to generate a series of spectra at different temperatures and for each band. The temperatures of the spectra were between log T = 5.5 to 6.7, with temperature steps of 0.05 dex (25 different temperature values). For each band, a single spectrum is composed of 256 points (bins) with an energy separation of 0.50 eV and 1.33 eV across in the 0.22 keV band and 0.70 keV band, respectively. We calculate the contribution to the X-ray intensity in each zone of hot gas by multiplying the emissivity from the most appropriate of the tabulated spectra (as determined by the temperature of the zone) by the emission measure (the product of gas density squared and length of the sightline across the zone).

The radiative transfer along the line of sight is simplified because the emitting plasma has a low optical depth and the absorbing material neither scatters nor emits X-rays. Therefore, along a line of sight, radiative transfer amounts to discrete additions of source spectra or discrete absorption of the net incoming spectral energy distribution. We assume that absorption is produced by gas below temperatures of 300,000 K, although nearly all of the attenuation is due to much cooler material by virtue of greater column densities. The opacity is calculated at the central energy for each of the 256 bins within each band, and the path length of the sightline across the zone. For the absorption cross-section, we used the Morrison & McCammon (1983) prescription, which is of the form \((c_0 + c_1 E + c_2 E^2)E^{-3} \times 10^{-24} \text{ cm}^2\), where \(c_0\), \(c_1\), and \(c_2\) are the coefficients of an analytic fit and \(E\) is in keV. The calculations of the intensity are for a Galactic
The effects of an extragalactic X-ray background contribution (henceforth, XRB) to the calculated X-ray intensities are important, especially in the higher energy band and for directions of low absorbing column. For each line of sight at each position, we have added an intensity equal to \( E_0 e^{-\sigma_{eff}N_{cool}} \), where \( E_0 \) is the constant intensity emitted by the extragalactic background, and \( \sigma_{eff} \) is the effective cross-section (in units of cm\(^2\)). Unfortunately, \( E_0 \) is not known \textit{a priori}, but is estimated based upon an extrapolation from the XRB at higher energies; to account for this ambiguity, we consider multiple values of \( E_0 \). Estimates based on observations suggest that the XRB at \( 3/4 \) keV could be as much as 50 – 65% of the observed flux in some directions (Burrows & Mendenhall 1994). Therefore, for \( E_0 \) we used values of double and triple the median of the \( I_{0.70 \text{ keV}} \) (without an XRB) medians for the five strip surveys, or \( E_0 = 1.2 \) and \( 1.8 \times 10^{-5} \) (in our intensity units). Assuming an \( E^{-1} \) photon spectrum for the XRB, the flux-weighted mean energy for the XRB in the 0.532 – 0.873 keV band is 0.688 keV, and we use this energy to calculate a cross-section. Then, we compute the resultant additions for each value of \( E_0 \) to the 0.70 keV intensity with the cool gas (\( T < 300,000 \) K) column density at each line of sight, and plot these in Figure 4. Also, we have plotted the effect an XRB would have on the 0.22 keV energy band for a single value of \( E_0 \) in Figure 4. The mean energy in the 0.155 – 0.284 keV band with an \( E^{-1} \) spectrum is 0.213 keV, and we used a value of \( E_0 = 4.8 \times 10^{-5} \), which is three times the larger of the two \( E_0 \) used in the 0.70 keV band (and is consistent with an \( E^{-1} \) spectrum in a band with \( 1/3 \) the energy).

A stellar contribution to the diffuse Galactic X-ray intensity is not included in this analysis. The coronae of normal stars (e.g., dM stars) may produce as much as 10 – 20% of the diffuse Galactic X-ray emission in the 0.28 – 1.0 keV band (Caillault, Helfand, Nousek, & Takalo 1986), but \( \lesssim 3\% \) in the 0.15 – 0.28 keV band (Rosner et al. 1981). Also, since stellar point sources are subtracted from recent X-ray surveys, such as the ROSAT studies of diffuse Galactic emission, we believe that this omission of a stellar contribution will not have strong consequences for our analysis.

The resulting X-ray intensities are given in units of \( 2.078 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcmin}^{-2} \) (Fig. 4). This intensity corresponds to \( \sim 1 \text{ ct s}^{-1} \text{ arcmin}^{-2} \) over the entire 0.1–2.4 keV ROSAT band (Snowden et al. 1994b). Some sample conversions between our intensity and the cts s\(^{-1} \) arcmin\(^{-2} \) received by ROSAT, using the on-axis energy response function, are given in Table 3 in each of the R2 and R4 bands. We also include in Table 3 a conversion of our intensity to cts s\(^{-1} \) in the Wisconsin C and M\(_1\) band, from the response to an \( E^{-1} \) spectrum in Table 3 (although the response is not very sensitive to the spectral index of the incident photons) in McCammon et al. (1983). These conversions are needed for the data in all of the figures with X-ray intensities and also in Tables 4 and 5, where we list the same statistical quantities for each X-ray band (with an XRB) as we did in Table 2 for the \( N_{H,1} \) data.

### 4.4. Contributions to the X-Ray Emission as a Function of Depth

One of the important uses of the simulations is to better understand the contributors to the X-ray emission as a function of distance from the observer. In general, we find that the ISM within 1 kpc of the observer contributes \( \gtrsim 90\% \) of the resultant X-ray intensity, at 0.22 keV and 0.70 keV for both midplane and high-latitude lines of sight (see Figure 5, which is a plot of cumulative X-ray intensity vs. distance and should be “read” starting from the right side of each panel). The two lines of sight displayed in Figure 5 illustrate the inhomogeneous nature of the ISM, with one line of sight from Bubble 2 in the direction of...
Bubble 3 (at a latitude of -33°R from a line parallel to the midplane, note that for Position 2, $z = 230$ pc), and the other from Position 4 at a latitude of 1°L. From the position within Bubble 2 (see Figure 5a), the ISM at a distance of 300 – 700 pc contributes much of the X-ray intensity, this is where the line of sight crosses Bubble 3. The diminution of X-ray intensity at 300 pc, which is significant only in the softer 0.22 keV band, is caused by some very dense, cold gas at the boundary between Bubbles 2 and 3. From Position 4 at $b = 1°$L (see Figure 5b), the line of sight crosses Bubble 3 and enters a clump of cold gas (at $x, z = 142 - 145, 200$) with $N_{\text{H}1} \approx 1.5 \times 10^{21}$ cm$^{-2}$ (roughly 10% of the total $N_{\text{H}1}$ for the line of sight). The constant 0.70 keV intensity within a distance of 300 pc in Figure 5b is caused by gas that is warm, but not hot enough to contribute substantially to the X-ray intensity. The X-ray intensity from Bubble 3 is seen at $d = 300 - 500$ pc, with a decrease over 40 – 50 pc (4 – 5 zones) at the closer boundary of the bubble in both X-ray bands, and the 0.22 keV intensity is reduced to $10^{-8}$ in these units (and is not shown in Figure 5b).

Since the grid is 2 kpc across, and the line of sight extends to 5 kpc, features for the line of sight close to the midplane repeat, e.g. the contributions of Bubble 3 are also seen at $d = 2400$ pc and $d = 4400$ pc in Fig. 5b. Similarly, contributions from Bubble 1 are seen at $d = 1100 – 1200$ pc and $d = 3100 – 3200$ pc, and contributions from the hot gas at the left edge of the grid (crossing the line of sight at $x, z = 4 – 26, 201$) are seen at $d = 1500 – 1750$ pc and $d = 3500 – 3750$ pc, while attenuations from near Position 5 are seen at $d = 900$ pc and $d = 2900$ pc (no X-ray intensity is emitted beyond $d = 4700$ pc).

The two lines of sight described by Figure 5, which are typical, indicate that at 0.70 keV, emission contributions from structures beyond 2 kpc will be difficult to study. At Position 4 (Fig. 5b), the considerable integrated emission measure beyond 1.5 kpc contributes less than 2% of the observed emission, and studying a structure that is defined by such a small fluctuation against the X-ray background is likely to be impossible. Other lines of sight are less favorable (Fig. 5a), and at 0.22 keV, contributions beyond the local or adjacent bubble are negligible.

Variations of the Galactic X-ray intensity in our model are caused primarily by variation within the local bubbles, which is caused by both the size of and the temperature variation within each bubble, but also with a contribution of non-local (but Galactic) intensity that varies with latitude. Bubbles of hot gas created in the hydrodynamical simulation naturally have non-uniform shapes and contain gas at a variety of temperatures (see Figure 1c). For example, the three-lobed structure of Bubble 3 leads directly to three broad maxima in the X-ray strip surveys (Figures 4h and 4i). This is consistent with the success of the displacement model (Snowden et al. 1990) at reproducing much of the X-ray background at energies below 0.284 keV. Viewing the evolution of the simulation shows that much of the hot overpressured gas in Bubble 3 is expanding into regions of colder and denser material, similar to what is envisioned in the displacement model.

The additional X-ray intensity from hot gas beyond each of the simulated local bubbles has a large variation with latitude. For example, in Figure 4e at 0.22 keV from Bubble 2 the non-local contribution (that can be estimated in Figures 4b, 4c, 4e, 4f, 4h, and 4i, by comparing the total intensity without an XRB, the solid line, with the local contribution, the dashed line) varies from zero at most latitudes to as much as 1 dex near $b = 30°$L and -20°L. Most of this non-local intensity is from hot gas that is near Bubble 2 (at $x, z = 80, 230$), but is beyond some intervening cool gas from the observing position within the bubble. This large variation of the non-local intensity is consistent with an observational estimate that the halo is eight times brighter toward Draco than toward Ursa Major at $1/4$ keV (SHJLMS). The non-local contributions in the 0.70 keV band are often larger than those in the 0.22 keV band for each of the three bubbles, particularly as seen from within Bubble 1 (see Figures 1b and 1c), which contains relatively cooler hot gas ($T \sim 5 \times 10^5$ K, see Table 1) than the other two bubbles. In this case, the larger increment in the
harder band is primarily a consequence of the lower intensity of this cooler hot bubble in the higher energy bands.

4.5. The Angular Distribution of the X-Ray Emission

From Figure 4, it is obvious that our model generates X-ray emission that is in general both fainter than in the observations and has a larger angular variation. These failings suggest that we are in a Local Bubble that is more homogeneous and has a higher emission measure than any of the bubbles in our model (although Bubble 3 appears closest to observations in a number of categories). We discuss this in greater depth in §5 with regard to future work. In this section, we examine some of the specific details of the angular variation of the simulated X-ray emission, as well as the relative hardness in the two bands.

The angular distribution of the 0.22 keV model X-ray emission shows many interesting details from each of the bubbles (in Figures 4b, 4e, and 4h). Due to the short mean free path of photons in this soft X-ray band, the size and shape of the bubble primarily determines the nature of the modeled X-ray emission. In general, this means that the maximum and minimum X-ray intensity within each strip scan can occur at any latitude. For example, Bubble 1 has an overall maximum near 0°L with a secondary peak near -60°L; both of these are included in the non-local emission from the large nearby bubble that subtends latitudes between 10°L and -90°L from Bubble 1. From Figure 4b, the minimum values seen from Bubble 1 are in the latitude ranges 30°L – +90°L and -80°R – 10°R. These low intensities are caused by a small path length across the bubble and a lack of hot gas beyond the Bubble 1 in these directions (see Figure 1).

For Bubble 2, the peak in the 0.22 keV emission is at latitude 45°L, which contains the ridge of very high temperature gas (4 – 5 × 10^6 K) within Bubble 2. Note that there is also a broad secondary maximum 180° away from this (at b = -45°R), a result of the shorter path length through the high temperature ridge that is wider in that direction. The minimum for the 0.22 keV intensity in Bubble 2 is at b = -30 – -40°L, and this is in the direction of some very cold (and presumably dense) gas roughly between Bubbles 1 and 2.

The 0.22 keV intensity for Bubble 3 is brightest near one of the poles (+90°) and the deepest minima is near the plane (0°L), although the situation is reversed toward the other pole and plane crossing; this is a consequence of the three-lobed shape of Bubble 3. Of particular note is that this is the simulated bubble with the most smoothly varying X-ray emission, because the observations have even smaller fluctuations.

A statistical analysis of the angular distribution of the I_{0.22 keV} emission with an added XRB is presented in Table 4, where there are some similarities in the properties of the three bubble locations, especially as compared to Position 4 (located in warm gas) or Position 5 (located in cold gas). The positional variation is smallest in the maxima (column 6 of Table 4), and increases monotonically as the statistic describes lower ordinal values of X-ray intensity (ending with a largest range of values of 0.22 keV model data in the minima — column 2 of Table 4). As with the N_{H I} data, Bubble 3 has the closest distribution of 0.22 keV model data to that of the observational strip from the Wisconsin C band, but the model has a much larger range than the observations (cf. a δ_{I} of 0.9 in the model vs. 0.4 in the data).

In the model X-ray emission at the harder energy, 0.70 keV, we have seen that contributions to the X-ray intensity come not only from the local bubble, but from within 2 kpc of the observer. Along this path length, the competition between emission and absorption determines whether the X-ray intensity has a local maximum or minimum near the plane. For the conditions in our simulations, the two effects are comparable, and although we generally find a brightening near the plane at 0.70 keV, there are clear
examples of absorption effects near the plane as well as bright regions at moderately high latitudes. As for the 0.22 keV emission above, we now examine the angular distribution in the three hot bubbles.

Since Bubble 1 is a region of cooler hot gas ($\sim 5 \times 10^5$ K), most of the emission at 0.70 keV is from beyond the local bubble at most latitudes. The brightest regions are toward the plane, although the hot gas just to the left of Bubble 2 in Figures 1a and 1b (at $x, z \approx 80, 230$) generates a brighter spot at a latitude of 50$^\circ$R. In general, for Bubble 1 the 0.70 keV emission from the local bubble is so small that it is dominated by the XRB.

For Bubble 2, much of the emission at 0.70 keV is from the local bubble, as was the case for the 0.22 keV intensity. Non-local contributions are usually located near the plane, $|b| = 0^\circ$ (note that this is 250 pc above the midplane in Figure 1). Two main sources of this non-local emission are the hot gas near $x, z = 20, 210$ and a dim version of Bubble 2 from 2 kpc away, which is a consequence of the periodic boundary conditions. There is some bright 0.70 keV emission at moderate latitudes, specifically at $b = 30^\circ L - 60^\circ L$, from the ridge of hot gas within Bubble 2 and the hot gas next to Bubble 2; $-40^\circ L$, from the hottest gas at $x, z = 165, 125$ in the large bubble next to Bubble 1, and $-30^\circ R - 60^\circ R$, from Bubble 3.

For Bubble 3, the 0.70 keV intensity is dominated by the hot local bubble. Even one of the brighter regions, toward $b = -50^\circ R - 70^\circ R$, that appears to be non-local emission is from the same bubble, since the sightline from the position within the bubble crosses the finger of cold gas at $b = -90^\circ$. Also, the three-lobed structure that is seen at 0.22 keV is less evident, because one of the lobes (toward $b = +90^\circ$) is at a significantly lower temperature than the rest of the bubble. The largest, highest temperature lobe is the brightest region between $b = -70^\circ R$ and $20^\circ R$ (see Figure 1).

The $I_{0.70 \text{ keV}}$ strip scans for Bubbles 1, 2, and 3 shown in Figures 4c, 4f, and 4i contain a dip to differing degrees in the intensity near the midplane. This decrease in 0.70 keV intensity is most easily seen from Bubbles 1 and 2, and to a lesser extent from Bubble 3. This dip exists in observations; it is seen both in the Wisconsin M$_1$ map (McCann et al. 1983) and in the $3/4$ keV map in the ROSAT All-Sky Survey (Snowden et al. 1995b). While the strip scan that we display and analyze from the Wisconsin M$_1$ data does not have a significant dip near the midplane, the entire M$_1$ map does contain this feature. The strip that we are concerned with goes through the midplane at longitudes of 90$^\circ$, which is near the Cygnus Loop, and 270$^\circ$, which has had (high brightness) data associated with the Vela/Puppis SNR removed; therefore, the dip is not as easily detected in the strip we chose.

The statistical quantities of the 0.70 keV model data in Table 5 are most dependent on the spatial distribution of the hottest gas in the simulation within approximately 2 kpc of each position. Since the simulated region is only 2 kpc wide and the hottest gas ($> 2 \times 10^6$ K) is confined to within 400 pc of the midplane, each of our five positions is close enough to all of the hottest gas that each position detects the same sources of 0.70 keV intensity. As with the 0.22 keV data, the range of the model data decreases for the higher ordinal statistics, with the maxima of the 0.70 keV model data in Bubbles 1 – 3 and Position 4 within $\pm 15\%$ of their mean. All of our statistical quantities of the model 0.70 keV band intensities are considerably smaller than their counterparts in the observational data. The overall dimness of the 0.70 keV model data suggests that the hot gas in the model is cooler than the Galactic hot gas phase, which could be remedied by a higher energy injection rate, and we discuss this further in §5.

Neither of the ranges of the 0.22 keV and 0.70 keV model data in Tables 4 and 5 compare well with the ranges of the observational data in Sanders et al. (1977) (B band, $E = 0.1 - 0.18$ keV, and C band data), Burrows & Mendenhall (1991) (C band), SHJLMS (C band), and in the $1/4$ keV and $3/4$ keV ROSAT All-Sky Survey maps (Snowden et al. 1995b). The large scatter in both the observations and the model
prevents a simple model of the form \( I = I_0 + I_1 e^{-\sigma N_{HI}} \) from reproducing all of the data (particularly from within a bubble), where \( I_0 \) is the local X-ray intensity and \( I_1 \) is the X-ray intensity at some distance removed from the observer and is completely attenuated by the entire H I column. While the ranges in the model data are larger than that for a simple model, they are also larger than in the observations. For example, there is a small ratio of maximum to minimum of only two to five in the \( 1/4 \) keV (or C band) intensity in the observations and the smallest of the ratios from the simulation is of order 2 dex. Even bright supernova remnants that are excluded from observational datasets, that increase the maximum X-ray intensity by as much as 1 dex (e.g. ROSAT observations of the Vela SNR by Bocchino, Maggio, & Sciortino (1994)) will not help our model fit the observations. This is because the brightest parts of the X-ray sky only cover a small fraction of the sky, while in our model the brighter regions are large scale features.

Another commonly computed parameter is the hardness ratio, which is defined (for the two X-ray bands computed in this paper) as \((I_{0.70 \text{ keV}} - I_{0.22 \text{ keV}})/(I_{0.22 \text{ keV}} + I_{0.70 \text{ keV}})\). The hardness ratio is shown at each position with respect to latitude in Figures 6a – e and with respect to the column density of H I in Figures 7a – e, and the hardness ratio of the strips of the Wisconsin data that we have used previously are shown in Figures 6f and 7f. In the plots from our model, we have added a small value to the denominator of the ordinate to allow for cases where there is no X-ray intensity in either band (for cases with no XRB).

The X-ray intensities appear to be a good discriminator when comparing models to data, but the hardness ratios appear to be an even more sensitive indicator of the success or failure of a calculation to reproduce the data. As we show, the emission from the models appears to be significantly softer than those of the data, with the exception of Position 5. Of the bubbles, Bubble 3 has the largest fraction of lines of sight with a distinctly positive hardness ratio. The overall hardness of the X-ray spectrum at Position 5 is caused by a large column of cold, dense gas within 60 – 70 pc of the position that prevents softer X-rays from reaching the center of the cold gas. The low temperature of Bubble 1 (compared with the average temperature in Bubbles 2 and 3) creates the softness of the local gas in Bubble 1 (the dashed line in Figure 6a), while only isolated pockets of the hottest gas create maxima in the hardness plots. For example, from the position in Bubble 2 the hot gas in Bubble 3 subtends the latitude range \( b = -60^\circ R - -15^\circ R \), and only the hottest gas in the rightmost lobe of Bubble 3 (at \( b = -35^\circ R \)) has a hardness ratio > -0.50 (see Figure 6b). As another example, the hardest X-ray emission seen from Bubble 2 comes at an angle near \( b = 0^\circ L \), where the 0.70 keV emission is from Bubble 2 itself. The dip near the midplane of the 0.70 keV band is also apparent in the hardness ratio in Bubbles 1, 2, and 3 (only at \( b = 0^\circ L \) in Fig. 6b). As displayed in Figure 5, including the XRB (which has an unattenuated hardness ratio = -0.50) hardens the resulting X-ray spectrum at high latitudes from Bubble 1, and Positions 4 and 5 (see Figs. 6a, 6d, and 6e).

Despite the small angular scale dip in the 0.70 keV intensity near the midplane, the emission usually hardens near the midplane (Figure 6), which agrees with a well-know observational result, i.e. that all-sky X-ray maps become less pole-dominated as the photon energy is increased (see McCammon et al. 1983). Since latitudes near the midplane are associated with larger \( N_{HI} \), we have searched for a correlation between hardness ratio of the X-ray intensities (without the XRB) and \( N_{HI} \) (Figure 7), and this is only strongly evident from Positions 4 and 5 (Figures 7d and 7e). Adding the XRB does not change this result much: specifically, the hardness ratio at low \( N_{HI} \) sightlines is raised from near -1.0 to the XRB value of -0.5.
4.6. Anticorrelation Between H I and X-Ray Emission: Models vs. Observation

The model data displayed as a function of latitude shows that there is a complex mix of correlation and anticorrelation between the N$_{\text{H I}}$ and I$_x$ (after the extragalactic background has been added). In addition, the plots in Figures 4a and 4b (for Bubble 1) of X-ray intensity in either band demonstrate that the intensity can appear correlated with N$_{\text{H I}}$ rather than anticorrelated, at least on scales of tens of degrees. Specifically, the peak in N$_{\text{H I}}$ at $b = 0^\circ$L for Bubble 1 coincides with a large scale rise in the X-ray intensity in both bands. However on a smaller angular scale, anticorrelation does exist, e.g. the N$_{\text{H I}}$ maximum is coincident with the local minimum in intensity (in both X-ray bands) at $b = 0^\circ$L in Figs. 4a – c. In this subsection, we shall use Kendall’s $\tau$ to quantify the correlation between the N$_{\text{H I}}$ and I$_x$ in each X-ray band.

A combination of two competing effects creates the combination of correlation and anticorrelation between X-ray intensity and N$_{\text{H I}}$ mentioned above. First, dense regions of cold gas prevent hot gas from expanding as quickly as would otherwise be the case, allowing the hot gas to maintain its temperature; this generates a correlation between X-ray intensity and N$_{\text{H I}}$. Another source of correlation is that a shock moving into denser gas generates a higher emission measure plasma than a shock moving into a lower density region. Alternatively, regions of dense gas also absorb non-local contributions to the X-ray intensity, which improves the anticorrelation. From the strip survey data of model N$_{\text{H I}}$, I$_{0.22}$ keV, and I$_{0.70}$ keV in Figure 4, it appears that the former effect is somewhat more dominant for the positions within bubbles, but both are apparent.

For illustrative purposes, we have plotted the X-ray intensity (including the larger XRB value in the 0.70 keV band) against the H I column density (see Figure 8) for Positions 3 and 4 in both X-ray bands, as well as the observational data from the DL and Wisconsin surveys. Since some of the 0.22 keV model data are coincident with the C band data in the plot, we have put the observational data in separate panels from the model data to assist in the comparison. Comparing the model data from each position shows that typical X-ray intensity in Figure 8 as observed from within Bubble 3 is much larger than from Position 4. The X-ray intensities are so weak from Position 4 that some of the simulated data are not plotted in the figure. The observational data has a much narrower distribution (in both coordinates, but particularly in the X-ray distribution) than any of the model data. However, there is a subsample of the 0.22 keV model data that seems to match well with the entire C band strip, even to the constant X-ray intensity feature that extends from log N$_{\text{H I}}$ $\sim$ 20.5 – 22.0. Even though this is coincidental, it may suggest that the observations could be fit by a version of this model without too many modifications. No such coincidence is found between the M$_1$ band data and the 0.70 keV band data; the model data, even for Bubble 3 — the most like the observational data (see Figure 8c), are roughly 1 dex too faint.

The frequency of correlations or anticorrelations between the column density of H I and the X-ray intensity can be quantitatively discussed by computing the non-parametric correlation Kendall’s $\tau$ (e.g., Press et al. 1989) between N$_{\text{H I}}$ and I$_x$. This statistic yields a value of -1 if both datasets are completely anticorrelated, 1 if they are completely correlated, and 0 if there is no correlation.

From Kendall’s $\tau$, one can compute the probability of obtaining a specific $\tau$ from uncorrelated datasets (the null hypothesis). In Table 6, we list both Kendall’s $\tau$ and this probability for the complete N$_{\text{H I}}$, I$_{0.22}$ keV, and I$_{0.70}$ keV model datasets for each of the five positions. Since N$_\text{cool}(b)$ is not a well-observed quantity, we have used our computed values for N$_{\text{H I}}$ in this comparison. In addition, we have computed $\tau$ for subsets of the data that are separated by the same angular scale, for as many subsets as the angular scale would allow (2 subsets of 360 data points separated by $1^\circ$0 degree, 3 subsets of 240 points separated by $1^\circ$5 degrees, etc.). We did this for each subset with angular separations between 0$^\circ$5 and 10$^\circ$0 in
half-degree increments, and find that all of the \( \tau \)'s remain roughly constant as angular separation is varied, although the range in \( \tau \) increased as the separation increased (and the number of data points in the subsets is decreased). After deleting the data from the DL \( N_{\text{H}} \, 1 \) strip at the same latitudes where data had been removed from the Wisconsin survey, we have computed the Kendall’s \( \tau \) of the strips from the observational dataset. These values are placed in columns 2 and 6 in the row labeled “W” in Table 6.

The Kendall’s \( \tau \) reveals a distinct difference in the correlation of the X-ray intensity and \( N_{\text{H}} \, 1 \) for each of the two X-ray bands without an XRB (column 2 for the 0.22 keV band and column 6 for the 0.70 keV band in Table 6). This difference is explained both by the different mean free paths of 0.22 keV and 0.70 keV photons, and by the spatial distribution of the hottest gas. The three positions within bubbles of hot gas have X-ray intensities in the 0.22 keV band that are either positively correlated or uncorrelated (i.e., the probability that the specific \( \tau \) could be from completely uncorrelated data is greater than 30%) with \( N_{\text{H}} \, 1 \), while Position 4 (in warm gas) and Position 5 (in cold gas) have distributions that are somewhat anticorrelated. This situation is reversed when the 0.70 keV intensity data are compared to the simulated \( N_{\text{H}} \, 1 \) data; the positions within bubbles are more anticorrelated than for Positions 4 and 5, which show a significant correlation. This occurs because the 0.70 keV intensity is dominated by the hottest gas, which rarely exists at high latitudes for positions outside of a bubble, since the hottest gas is contained close to the midplane. The largest anticorrelation of \( N_{\text{H}} \, 1 \) and 0.70 keV intensity is in Bubble 3; one contribution to this anticorrelation is the 0.70 keV dip near \( b = -90^\circ \) that coincides with a dense finger of cold gas that separates two lobes in Bubble 3 (Figs. 1 and 4i).

The anticorrelation from the observational data, as described by the Kendall’s \( \tau \) in the last row of Table 6, is stronger than that from any of the positions we have chosen from the simulation, and is much stronger than any in the 0.22 keV band. The large difference between the observed and model anticorrelations in the C band is most likely caused by the shape and orientation of the bubbles that we have analyzed. Since none of Bubbles 1, 2, or 3 is larger in vertical extent than in the midplane, as the Local Bubble is thought to be (from the pole-dominated emission in Be, B, and C bands), the anticorrelation of \( I_{0.22 \, \text{keV}} \) with \( N_{\text{H}} \, 1 \) in our model is understandably smaller than the observational values. None of the model data has a similar decrease in the anticorrelation when the strip from the Wisconsin C band is replaced by the strip from the \( M_1 \) band in the comparison with the DL \( N_{\text{H}} \, 1 \) strip, but this is mainly caused by the lack of a good fit for the models in the softer band. However, the anticorrelation between the observational \( N_{\text{H}} \, 1 \) and \( M_1 \) data is most nearly matched by Bubble 3.

In all situations, additional X-ray emission from an XRB causes the distributions to be more anticorrelated, with a result that all of the \( \tau \)'s are negative for the largest values of \( E_0 \) used in each band (columns 4 and 10 in Table 6). This occurs despite the significantly positive values of \( \tau \) from positions 4 and 5 at 0.70 keV without the XRB (column 6). The most anticorrelated distribution of the model data is between \( I_{0.22 \, \text{keV}} + E_0 \) and \( N_{\text{H}} \, 1 \) (column 4) at Position 5, caused by the very large \( N_{\text{H}} \, 1 \) at all \( b \) (minimum log \( N_{\text{H}} \, 1 \) ~ 20.5) and the large effective cross-section at low X-ray energies.

To summarize this subsection, our model generates a combination of correlation and anticorrelations between \( N_{\text{H}} \, 1 \) and the intensity in both of the soft X-ray bands that we have computed. However, for observers within bubbles of hot gas there is a statistical tendency for anticorrelations to be favored, and this trend is strengthened by the addition of an XRB.
4.7. X-Ray Model Spectra

In this section, we will discuss simulated spectra computed at a latitude of +90° from Bubble 2 and Position 4. These lines of sight will show the differences between a line of sight that has many zones of hot gas with a large range of temperatures, including some very hot gas in Bubble 2, and a line of sight that passes through a superbubble in which the hot gas has cooled to a relatively low temperature. The model spectra (see Figure 9) were computed with a high spectral resolution, with $E/\Delta E \sim 500$ for each band (435 for the mean energy in the 0.22 keV band, and 530 in the 0.70 keV band).

The computed spectra are displayed in Figure 9, as well as the spectra convolved with energy resolutions, $E/\Delta E$ (where $\Delta E$ is the FWHM of a Gaussian), of 30 and 100. For the line of sight from Bubble 2, which contains some very hot gas, we find evidence for highly ionized species (see Figs. 9c, 9i, and Table 7). Such highly ionized gas is not present for the line of sight through the cooled superbubble (Figs. 9f, 9l, and Table 7), which passes through the relatively cool gas (at $T \sim 5 \times 10^5$ K) of the superbubble at $x = 175$ (see Figure 1a).

A single-temperature spectrum usually fits each of the model spectra. We have compared the highest resolution spectra shown (Figs. 9c, 9f, 9i, and 9m) with single temperature spectra (assuming no intervening absorption) described in §4.3 by both matching continua by eye and minimizing the usual Kolmogorov-Smirnov $D$-statistic. From this analysis, we find that a Raymond-Smith plasma of log $T = 6.30$ is similar to both spectra from Bubble 2 (Figs. 9c and 9i), while log $T = 5.70$ matches the 0.22 keV band spectrum from Position 4 (Figure 9f) and log $T = 5.95$ does so for the 0.70 keV band spectrum (Figure 9l). In each of the simulated spectra plotted in Figure 9, we have added an XRB spectrum with two characteristics: 1) an $E^{-1}$ slope (with no emission lines), and 2) that the sum of intensities in each band is equal to the XRB intensity that we estimated in §4.3 (the larger of the two values in the 0.70 keV band).

We have convolved each of the single temperature spectra with an energy resolution of $E/\Delta E = 100$, and plotted the result (the dotted line) in Figs. 9b, 9e, 9h, and 9k. From these single temperature plots, one sees that the 0.70 keV band spectra from Bubble 2 is not well fit by a single temperature (Fig. 9h). This results agrees with one from the K-S comparison, that the $D$-statistic was minimized at two temperatures (log $T = 6.25$ and 6.45). Despite the indication that absorption in the softer band might have caused the multi-temperature “fit” in the 0.70 keV band (while this is not so in the 0.22 keV band), this is not true because there is no gas at the higher temperature beyond Bubble 2 itself (at $b = +90°$).

The spectra at different energy resolutions demonstrate the need for high resolution X-ray spectra. From the spectra in Figure 9, we show that line identification can be accomplished only with an energy resolution greater than between 30 and 100, while the detection of the jagged continuum (caused by atomic line edges, e.g. 0.666 keV and 0.740 keV in Figure 9h) requires an $E/\Delta E$ of at least 300. Some of the current or planned X-ray missions include the capability to conduct high resolution spectroscopy (e.g., DXS, LEXSA, and XMM), with $E/\Delta E$ of about 100.

5. Concluding Remarks and Directions for Future Work

The calculations of a variety of model $\text{H I}$ and X-ray properties has provided several insights into the nature of our interstellar medium. For the $\text{H I}$, the observed scale height is reproduced in the models, as is the general shape of $\text{H I}$ with latitude (for Bubble 3), but the model $N_{\text{H I}}$ is too low at several high latitude locations. From within hot bubbles, the median $N_{\text{H I}}$ is similar to that observed from the Sun, even though both values are below the mean $N_{\text{H I}}$ through the disk (as an initial condition, the mean $N_{\text{H I}}$
in the simulations of RB was taken to be equal to the value at the Solar circle). This difference, which in the model has the median value of \( N_{\text{HI}} \) a factor of \( 2.5 - 6 \) lower than the mean, arises because \( \text{H\,I} \) has a low filling factor and there are relatively few discrete \( \text{H\,I} \) structures along a line of sight out of the disk.

Our calculations of model X-ray intensities show that the emission in the two soft X-ray bands is dominated by hot gas that is close to the observing position at 0.22 keV (\( \lesssim 0.5 \) kpc). At 0.70 keV, the contribution from beyond the local bubble can dominate the emission, although the non-local contribution varies widely with latitude; nearly all the disk emission originated from \( \lesssim 2 \) kpc. Whereas substantial variation occurs in the X-ray intensity (roughly a factor of five or six in the Wisconsin C band and M1 band data), the variations in the calculated intensities are even greater, which points out a shortcoming in the model.

An examination of the relationship between \( N_{\text{HI}} \) and X-ray intensity shows a complex combination of correlations and anticorrelations. Aside from individual examples of each, we examined whether the two observables are generally correlated or anticorrelated in a statistical sense and sought to quantify the issue by calculating the nonparametric correlation Kendall’s \( \tau \). In the 0.22 keV band the \( N_{\text{HI}} \) and the X-ray intensity (without the XRB) are either uncorrelated or slightly correlated from positions in bubbles of hot gas, while they are anticorrelated from the positions of warm or cold gas, and this trend is reversed in the 0.70 keV band (again without the XRB). The explanation for these trends is a combination of a short mean free path of 0.22 keV photons and the proximity to the midplane of the hottest gas that dominates the 0.70 keV emission. However, as an XRB is added to the X-ray intensity, the two simulated data sets become increasingly anticorrelated. The Kendall’s \( \tau \) for the strip of Wisconsin C band data when compared with the DL \( N_{\text{HI}} \) strip scan showed a very large anticorrelation (\( \tau = -0.6 \)), that we feel is caused more by the larger vertical extent of the Local Bubble in the Galaxy than any flaw within our model. This anticorrelation is reduced when the M1 band is compared with the \( N_{\text{HI}} \) observational data (\( \tau = -0.15 \)), which is similar to the anticorrelation between the model \( N_{\text{HI}} \) and \( I_{0.70\text{keV}} \) data for Bubble 3.

We computed some spectra based upon the simulation, and found that despite various contributions along the lines of sight a one temperature Raymond-Smith spectrum often provided a satisfactory fit. Multiple temperature fits were required along certain lines of sight, although the ability to recognize a multi-temperature medium requires good signal-to-noise spectra with an energy resolution of \( E/\Delta E \gtrsim 100 \). This analysis argues for high energy resolution X-ray spectrometers, since an energy resolution of \( E/\Delta E \gtrsim 30 - 100 \) to resolve many of the spectral lines.

The failure to reproduce certain important H\,I and X-ray observations has pointed out a shortcoming of the models. For the H\,I, we find that the minimum \( N_{\text{HI}} \), which occurs at high latitude, is too low as seen from all five locations. In most, but not all locations, the calculated variation of brightness temperature is too great (e.g., the beam-to-beam fluctuations of the observations are less than of the model). In the X-ray band, the most pronounced shortcomings of the models are that the X-ray surface brightness is too low, and the range of X-ray variation is too great along the strip scans as is the range of X-ray hardness ratios. We consider whether these shortcomings would be alleviated by varying some of the model parameters (e.g., the supernova heating rate) or by adding physics neglected in the existing model (e.g., magnetic fields).

A hotter, more pervasive model of the ISM would solve many of the X-ray deficiencies of this model: it would narrow the range of the X-ray intensity strip scans, by increasing the intensity of the lowest values in the 0.22 keV band, and it would raise all of the intensities in the 0.70 keV band (that would in turn increase hardness ratios). An increase in the volume filling factor of hot gas would occur if the true supernova heating rate was a bit larger than we had assumed (this number is probably unknown by a factor of three).
However, increasing the hot gas filling factor would probably reduce the volume filling factor of the neutral gas (see model F in RB), thereby reducing the high latitude $N_{\text{HI}}$, which is already too low.

The addition of magnetic fields to the simulations holds the possibility of solving the greatest shortcomings of the model. Magnetic fields can help confine hot gas in bubbles, making it more difficult for such bubbles to break out of the disk. This additional confinement should lead to higher temperatures, densities, and pressures in the bubbles and larger local emission measures, which would raise the X-ray intensities of the models. If breakout is less common, then the overlying H I layer will have fewer “holes”, so there would be a reduction in the number low values of $N_{\text{HI}}$ at high latitudes. We plan to investigate whether these expectations are borne out by quantitative calculations. The significance of magnetic fields on our models will be investigated in a future set of calculations, which will incorporate the powerful diagnostics provided by the X-ray and H I observations.

The authors would like to thank John Raymond at CfA for the use of the X-ray emission code, Mike Norman of the Laboratory of Computational Astrophysics for providing the hydrocode ZEUS, Jay Lockman for providing the DL $N_{\text{HI}}$ FITS file, Wilt Sanders for providing FITS files of the Wisconsin survey C band and M1 band data, and Dave Davis for calculating the ROSAT conversions in Table 3. Additionally, we gratefully acknowledge David Burrows (the referee) for many helpful suggestions from which the final version has benefited greatly.
Table 1. Local Characteristics of Positions

| Position # | (x, z) (pc) | height (kpc) | area (kpc²) | ⟨n⟩ (cm⁻³) | ⟨T⟩ (K) | P.med (cm⁻³ K) |
|------------|-------------|--------------|-------------|------------|---------|----------------|
| 1          | 55, 200     | 10           | 0.0188      | 6.435E-3   | 4.864E+5| 3210           |
| 2          | 100, 224    | 230          | 0.0705      | 3.617E-3   | 1.464E+6| 3060           |
| 3          | 135, 195    | 60           | 0.0382      | 6.788E-3   | 1.525E+6| 7540           |
| 4          | 175, 200    | 10           | 0.0707      | 0.03552    | 4.733E+4| 630            |
| 5          | 88, 200     | 10           | 0.0057      | 5.365      | 802.3   | 1420           |

Table 2. Variations of NH I

| Pos. | low (cm⁻²) | high (cm⁻²) | ⟨NH I⟩ | δN |
|------|------------|-------------|--------|----|
| 1    | 0.0225     | 0.313       | 1.046  | 3.358 | 248.2 | 6.678 | 3.059 |
| 2    | 0.0122     | 0.409       | 1.345  | 6.849 | 81.2  | 6.605 | 1.838 |
| 3    | 0.0395     | 1.212       | 3.566  | 8.187 | 140.6 | 9.372 | 1.892 |
| 4    | 0.0        | 0.103       | 0.801  | 4.111 | 231.5 | 6.961 | 2.832 |
| 5    | 2.8431     | 7.160       | 13.502 | 20.415| 235.3 | 16.663| 1.142 |
| DL   | 0.79       | 1.970       | 3.58   | 6.14  | 117.7 | 10.29 | 1.947 |

*In units of 10²⁰ cm⁻²*

Table 3. Conversion of Intensity Units to Counts per Second

| Energy (keV) | Wisconsin a | ROSAT band | log T (keV) | log NH I (cm⁻²) | ROSAT b  |
|--------------|-------------|------------|-------------|-----------------|----------|
| 0.22         | 2.76E5      | R2         | 6.0         | ...             | 1.8      |
|              |             |            | 6.0         | 20.0            | 1.2      |
| 0.70         | 2.01E4      | R4         | 6.0         | ...             | 0.30     |
|              |             |            | 6.0         | 20.0            | 0.28     |

*a To units of cts s⁻¹

*b To units of cts arcmin⁻² s⁻¹
Table 4. Variations of $I_{0.22\text{ keV}}^a$ with $E_0 = 4.8E-5$

| Pos. | min  | low quartile | median | high quartile | max   | $\langle I \rangle$ | $\delta_I$ |
|------|------|--------------|--------|---------------|-------|---------------------|-----------|
| 1    | 2.85E-5 | 5.43E-5     | 9.46E-5 | 1.86E-4       | 1.44E-3 | 1.29E-4            | 0.880     |
| 2    | 1.73E-5 | 5.93E-5     | 9.18E-5 | 1.89E-4       | 1.10E-3 | 1.46E-4            | 1.024     |
| 3    | 1.80E-5 | 7.61E-5     | 1.37E-4 | 3.57E-4       | 9.75E-4 | 2.40E-4            | 0.905     |
| 4    | 9.3E-12 | 1.46E-5     | 3.46E-5 | 4.99E-5       | 3.45E-4 | 4.27E-5            | 1.006     |
| 5    | 1.05E-14| 1.70E-8     | 1.50E-7 | 9.83E-7       | 4.22E-6 | 6.12E-7            | 1.447     |
| C    | 1.91E-4 | 3.68E-4     | 4.97E-4 | 7.34E-4       | 9.85E-4 | 5.30E-4            | 0.402     |

$^a$In units of $2.078 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$, see Table 3 for conversion to cts s$^{-1}$ arcmin$^{-2}$.

Table 5. Variations of $I_{0.70\text{ keV}}^a$ with $E_0 = 1.8E-5$

| Pos. | min  | low quartile | median | high quartile | max   | $\langle I \rangle$ | $\delta_I$ |
|------|------|--------------|--------|---------------|-------|---------------------|-----------|
| 1    | 8.80E-7 | 1.68E-5     | 2.01E-5 | 4.98E-5       | 4.48E-4 | 4.41E-5            | 1.219     |
| 2    | 1.23E-5 | 3.02E-5     | 5.49E-5 | 8.58E-5       | 5.08E-4 | 7.62E-5            | 0.881     |
| 3    | 2.33E-5 | 4.37E-5     | 6.33E-5 | 1.18E-4       | 4.00E-4 | 9.92E-5            | 0.803     |
| 4    | 4.26E-7 | 1.71E-5     | 1.78E-5 | 2.68E-5       | 3.88E-4 | 4.14E-5            | 1.502     |
| 5    | 5.61E-7 | 9.61E-6     | 1.39E-5 | 2.43E-5       | 1.69E-4 | 2.21E-5            | 1.036     |
| M1   | 3.22E-4 | 8.69E-4     | 1.03E-3 | 1.21E-3       | 1.71E-3 | 1.04E-3            | 0.240     |

$^a$In units of $2.078 \times 10^{-12}$ ergs cm$^{-2}$ s$^{-1}$ arcmin$^{-2}$, see Table 3 for conversion to cts s$^{-1}$ arcmin$^{-2}$. 
Table 6. Correlation of $N_{\text{H}1}$ and I — Kendall’s $\tau$

| Pos. | $\tau$ (2) | Prob. (3) | $\tau$ (4) | Prob. (5) | $\tau$ (6) | Prob. (7) | $\tau$ (8) | Prob. (9) | $\tau$ (10) | Prob. (11) |
|------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|------------|-----------|
| 1    | 0.084      | 7.31E-4   | -0.071     | 4.22E-3   | 0.072      | 4.07E-3   | -0.091     | 2.49E-4   | -0.136     | 5.14E-8   |
| 2    | 0.021      | 0.407     | -0.099     | 6.71E-5   | -0.078     | 1.75E-3   | -0.128     | 2.61E-7   | -0.148     | 2.66E-9   |
| 3    | 0.009      | 0.705     | -0.041     | 0.097     | -0.128     | 2.89E-7   | -0.202     | 4.99E-16  | -0.231     | 1.49E-20  |
| 4    | -0.111     | 8.96E-6   | -0.438     | 0.000     | 0.286      | 0.000     | 0.056      | 0.024     | -0.010     | 0.674     |
| 5    | -0.047     | 0.059     | -0.577     | 0.000     | 0.370      | 0.000     | -0.078     | 1.73E-3   | -0.145     | 6.31E-9   |
| W    | -0.588     | 0.000     |           |           |           |           |           | -0.161    | 7.37E-6    |           |

Table 7. Spectral Lines Seen in Figure 9

| Position | X-ray Band (keV) | Energy (keV) | Contributing Ion(s) |
|----------|-----------------|--------------|---------------------|
| 2        | 0.22            | 0.161        | Fe XIV, Si VIII, Fe XV |
|          |                 | 0.178        |                     |
|          |                 | 0.209        | Fe XIII, Fe XIV, Fe XV |
|          |                 | 0.251        | Si X, Si XI, S IX, Ar IX |
| 2        | 0.70            | 0.56         | O VII               |
|          |                 | 0.57         |                     |
|          |                 | 0.65         | O VIII              |
|          |                 | 0.73         | Fe XII              |
|          |                 | 0.83         |                     |
| 4        | 0.22            | 0.156        | Si VII, Fe XII, Mg VIII |
|          |                 | 0.164        | Ne VII, Mg VIII     |
|          |                 | 0.170        | Si VII, Si VIII     |
|          | 0.202 – 0.204   | S VII, Si VII, Si VIII, Si IX, Mg VII, Ne VIII |
REFERENCES

Allen, C. W. 1973, Astrophysical Quantities (London: Althone Press)
Bocchino, F., Maggio, A., & Sciortino, S. 1994, ApJ, 437, 209
Bowyer, S., Lieu, R., Sidher, S.D., Lampton, M., & Knude, J. 1995, Nature, 375, 212
Burrows, D.N., & Mendenhall, J. A. 1991, Nature, 351, 629
Burrows, D.N., Singh, K. P., Nousek, J.A., Garmire, G.P., & Good, J. 1993, ApJ, 406, 97
Caillault, J.-P., Helfand, D.J., Nousek, J.A., & Takalo, L.O. 1986, ApJ, 304, 318
Cash, W., Charles, P., Bowyer, S., Walter, F., Garmire, G., & Riegler, G. 1980, ApJ, 238, L71
Chiang, W.-H., & Bregman, J.N. 1988, ApJ, 328, 427
Chiang, W.-H., & Prendergast, K.H. 1985, ApJ, 297, 507
Dickey, J.M., & Lockman, F.J. 1990, ARA&A, 28, 215
Fabian, A.C., & Barcons, X. 1992, ARA&A, 30, 429
Garmire, G.P., Nousek, J.A., Apparao, K.M.V., Burrows, D.N., Fink, R.L., & Kraft, R.P. 1992, ApJ, 399, 694
Jahoda, K, Lockman, F.J., & McCammon, D. 1990, ApJ, 354, 184
Marshall, F.J. & Clark, G.W. 1984 ApJ, 287, 633
McCammon, D., Burrows, D.N., Sanders, W.T., & Kraushaar, W.L. 1983, ApJ, 269, 107
McCammon, D., & Sanders, W.T. 1987, ARA&A, 28, 657
Morrison, R. & McCammon, D. 1983, ApJ, 270, 119
Nousek, J.A., Fried, P.M., Sanders, W.T., & Kraushaar, W.L. 1982, ApJ, 258, 83
Plucinsky, P.P., Snowden, S.L., Aschenbach, B., Egger, R., Edgar, R.J., & McCammon, D. 1994, in AIP Conf. Proc. 313, The Soft X-Ray Cosmos, ed. E.M. Schlegel & R. Petre (New York:AIP Press), 3
Press, W.H., Flannery, B.P., Teukolsky, S.A., & Vetterling, W.T. 1989, Numerical Recipes, (Cambridge: Cambridge University Press)
Raymond, J.C., Cox, D.P. & Smith, B.W. 1976, ApJ, 204, 290
Raymond, J.C., & Smith, B.W. 1977, ApJS, 35, 419
Rosen, A., Bregman, J.N., & Norman, M.L. 1993. ApJ, 413, 137
Rosen, A., & Bregman, J.N. 1995, ApJ, 440, 634 (RB)
Rosner, R. et al. 1981, ApJ, 249, L5
Sanders, W.T., Kraushaar, W.L., Nousek, J.A., & Fried, P.M. 1977, ApJ, 217, L87
Snowden, S.L., Hasinger, G., Jahoda, K., Lockman, F.J., McCammon, D. & Sanders, W.T. 1994a, ApJ, 430, 601 (SHJLMS)
Snowden, S.L., Burrows, D.N., Sanders, W.T., Aschenbach, B., & Pfeffermann, E. 1995a, ApJ, 439, 399
Snowden, S.L., Freyberg, M.J., Plucinsky, P.P., Schmitt, J.H.M.M., Trümper, J., Voges, W., Edgar, R.J., McCammon, D. & Sanders, W.T. 1995b, ApJ, 454, 643
Snowden, S.L., Cox, D.P., & Sanders, W.T. 1990, ApJ, 354, 211
Snowden, S.L., McCammon, D., Burrows, D.N., & Mendenhall, J.A. 1994b, ApJ, 424, 714
Stanford, J.M. & Caillault, J.-P. 1994, ApJ, 424, 671
Stone, J.M., & Norman, M.L. 1992, ApJS, 80, 753
Verschuur, G.L., & Magnani, L. 1994, AJ, 107, 287
Fig. 1.— Grey scale images of gas temperature from a numerical hydrodynamical simulation (see RB). a) This image of gas temperature shows the locations of the five viewing positions, and displays some sample lines of sight at different latitudes. b) This figure also shows along the bottom and left axes the physical dimension of the grid, with sample lines of sight (5 kpc long) demonstrating straight paths in this physical space.

b) This image shows all the gas above 300,000 K, which we use as the lower temperature limit of X-ray emitting gas. None of the sightlines from any of the positions will cross the hot gas at the extreme top and bottom of the figure, but this gas will not contribute significantly to the X-ray intensity, because the extremely low density leads to a low emission measure from these zones. c) This image displays the gas temperature of “local” regions of a similar temperature to each of the viewing positions.

Fig. 2.— Comparison of a slice of $N_{\text{H I}}$ observational data and strip scans generated by the model. The dotted line is the data from the model and the solid line is a strip extracted from observational data (DL) that goes through both Galactic poles and longitudes of $90^\circ$ and $270^\circ$. The DL strip is shown starting with longitude $270^\circ$ at $0^\circ$R.

Fig. 3.— Histograms of the distribution of log $N_{\text{H I}}$. In panels a) – e), we show each set of 720 log $N_{\text{H I}}$ from the five positions that we analyzed; the panels are in the same order as Figure 2. In panel f), we show the distribution of the strip extracted from the DL data. Each of the histograms shown has a bin size of 0.1 dex. The lowest 1.5% of the lines of sight (i.e., 11) from Position 4 have $N_{\text{H I}} = 0.0$, and are not displayed in the histogram in panel d).

Fig. 4.— The column density of both the cool gas and the cold gas (H I), and X-ray intensity as a function of latitude. Panel a) – c) show strip scans for Bubble 1. In the top panel, only model data are shown, and the solid line represents log $N_{\text{H I}}$ while the dashed line is the column of all gas with $T < 300,000$ K ($N_{\text{cool}}$) within a distance of 5 kpc. In the middle panel, we show X-ray data from the 0.22 keV band, and in the bottom panel, we show X-ray data from the 0.70 keV band. In the panels that show X-ray intensity, the solid line is the model intensity from within 5 kpc while the dashed line indicates the X-ray intensity including an extragalactic component, using one value for $E_0$ in the $I_{0.22}$ keV plots and two values for $E_0$ in the $I_{0.70}$ keV plots (see §4.3). The dotted line shows the contribution from the local bubbles (as defined in Figure 1c).

The strip scan extracted from the Wisconsin C and M1 data are plotted as a dot-dash line (including some anomalously low values where high brightness data had been omitted) in each of the appropriate panels, with the data at longitude $270^\circ$ starting at $0^\circ$R. Panels d) – f) show strip scans for Bubble 2, with the same plots as panels a) – c). Panels g) – i) show strip scans for Bubble 3, with the same plots as panels a) – c).

Panels j) – l) show strip scans for Position 4, with the same plots as a) – c) without dotted lines since there is no local bubble at this position. Panels m) – o) show strip scans for Position 5, with the same plots as a) – c), again without dotted lines since there is no local bubble at this position.

Fig. 5.— The cumulative X-ray intensity component for the incoming direction is shown as a function of position along two lines of sight in the 0.22 keV (solid line) and 0.70 keV (dashed line) bands. The line of sight in panel a) displays model data from Bubble 2, at $b = -33^\circ$R out of the midplane (in the direction of Bubble 3). The model data in panel b) is from within the cool bubble at Position 4, along the midplane (at $b = 1^\circ$L). By proceeding from the initial position, 5 kpc from the observer (the right side of the diagram) leftward toward the observer (situated at $d = 0$), we see how the intensity increases through emission (regions of negative slope) and decreases by absorption of cool gas (lines of positive slope). The flat regions, where the intensity changes little over some distance along the line of sight, occurs where the gas is neither hot enough to contribute to the intensity nor dense enough to absorb it significantly.
Fig. 6.— The X-ray hardness ratio [here $\equiv (I_{0.70 \text{ keV}} - I_{0.22 \text{ keV}})/(I_{0.22 \text{ keV}} + I_{0.70 \text{ keV}})$] vs. latitude. Panels a) – e) display the model data from Bubbles 1, 2, and 3, and Position 4 and 5, respectively. The dot-dashed line in panel f) shows the hardness ratio of the Wisconsin C and M1 bands (without the omitted high-brightness data), where each band has been scaled to our intensity units. For the panels showing model data, the solid line displays the intensities in each band out to 5 kpc without an XRB, the dotted line (only in panels a – c) shows the ratio from the gas in the local bubble, and the dashed line shows the ratio for the intensities after adding an XRB, where we used the brighter XRB added to the $I_{0.70 \text{ keV}}$ data. The solid line at a hardness of zero shows where the dominance of the softer band gives way to that of the harder band.

Fig. 7.— The X-ray hardness ratio vs. $N_{\text{H}_1}$. Panels a) – e) display the model data from Bubbles 1, 2, and 3, and Positions 4 and 5, respectively. Panel f) shows the hardness ratio of the Wisconsin C and M1 bands (without the high-brightness data). Note that only the two positions near cool gas (Positions 4 and 5) have a strong dependence of X-ray hardness on $N_{\text{H}_1}$. The solid line at zero has the same significance as in Figure 6.

Fig. 8.— The X-ray intensities as a function of log $N_{\text{H}_1}$ for all lines of sight for Bubble 3, Position 4 and the observational data. Model data are plotted by open pentagons and observational data are filled squares. The panels a) and b) show log $I_{0.22 \text{ keV}}$ in Bubble 3 and Position 4, respectively, as panels c) and d) do for the log $I_{0.70 \text{ keV}}$ model data. The observational data are placed in the panels (not labeled) in the lower left and upper right to assist the reader in comparing the distributions along both axes.

Fig. 9.— Simulated X-ray spectra with an XRB at different resolutions for 2 lines of sight. The three resolutions correspond to $E/\Delta E = 30, 100, \text{ and } \sim 500$ (the unconvolved data) for $b = +90^\circ$ from Bubble 2 at 0.22 keV in panels a) – c), at 0.70 keV in panels g) – i), for $b = +90^\circ$ from Position 4 at 0.22 keV in panels d) – f), and at 0.70 keV in panels j) – l). The XRB has a slope of $E^{-1}$ and no emission lines. The dotted line in the $E/\Delta E = 100$ panels is a single temperature spectrum with the XRB added convolved to have this energy resolution; this line does not appear in panel k) because it is so close to the model data already plotted.