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A MODEL FOR THE DISTRIBUTION OF MÀTERIAL GENERATING THE SOFT X-RAY BACKGROUND

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ABSTRACT

We discuss the observational evidence relating to the soft X-ray diffuse background and present a simple model for its source and spatial structure. In this simple model with one free parameter, the observed $\frac{1}{4}$ keV X-ray intensity originates as thermal emission from a uniform hot ($T \sim 10^{6.0}$ K) plasma filling a cavity in the neutral material of the galactic disk which contains the Sun. Variations in the observed X-ray intensity are due to variations in the extent of the emission volume and therefore the emission measure of the plasma. The model reproduces the observed negative correlation between X-ray intensity and H I column density and predicts reasonable values for interstellar medium (ISM) parameters.

Subject headings: interstellar: matter — radiation mechanisms — X-rays: sources

I. INTRODUCTION

At X-ray energies, 0.1–100 keV, there is an appreciable diffuse background of cosmic origin. Between 2 and 10 keV, it is isotropic, clearly extragalactic, and can be represented by a power law. At lower energies, this radiation has a substantial cross section for photoelectric absorption by interstellar matter. As a consequence, early workers in the field anticipated that measurements at energies less than $\frac{1}{4}$ keV might provide information not only on sources of this radiation, but on the intervening absorbing gas of the Milky Way as well.

The earliest soft X-ray background (SXRB) measurements were examined for the signature of absorption: a negative correlation of X-ray intensity with H I column density ($N_{\rm H\,I}$). The trend was indeed found (Bowyer, Field, and Mack 1968; Bunner *et al.* 1969), but the strength of the absorption, the rate of falloff of SXRB intensity with increasing $N_{\rm H\,I}$, was weaker than expected from the known absorption cross sections. In addition, the measured soft X-ray intensity was far higher than an extrapolation of the spectrum observed above 2 keV. The source of this large excess intensity was initially assumed to be extragalactic, like the higher energy X-rays, while the weakness of the apparent absorption was explained by clumping of the H I gas. Subsequent observations have made it impossible for this model to satisfy all the constraints of the data: the signature of an absorbed extragalactic source fails inspection for details (McCammon *et al.* 1983).

The principal observational data available for energies less than $\frac{1}{4}$ keV may be summarized as follows: all-sky maps with 3° resolution (Marshall and Clark 1984; Fink 1990) and with 6° resolution (McCammon *et al.* 1983) exist for the C band (0.16–0.284 keV); all-sky maps with 6° resolution (McCammon *et al.* 1983) exist for the B band (0.13–0.188 keV); roughly 15 pointings exist for the yet lower energy Be band (0.078–0.111 keV) with a 15° field of view (Bloch *et al.* 1986; Bloch 1988; Juda 1988); earlier Be band measurements of lower statistical significance were published by Cash, Malina, and Stern (1976) and Stern and Bowyer (1979); the X-ray count rates are lowest ($\sim$30% of maximum) at low galactic latitudes and greatest at high northern latitudes—this alone would create a general negative correlation of the intensity with $N_{\rm H\,I}$, but even at constant latitude there is a definite negative correlation (with much scatter) of soft X-ray intensity with neutral hydrogen column density (Sanders 1976; Sanders *et al.* 1977); negative correlation attributable to shadowing is not seen either for the H I associated with the Small Magellanic Cloud or for the galactic H I toward it (McCammon *et al.* 1971, 1976), nor toward several other of the galactic H I features that have been examined in detail (Burrows *et al.* 1984); there is no correlation of soft X-ray color (C/B or B/Be band ratios) with SXRB intensity (or with neutral hydrogen column density; Burrows 1989); of these ratios, C/B has significant scatter (Fried *et al.* 1980), while B/Be has very little (Bloch *et al.* 1986; Juda 1988). Additional facts and observations are: the calculated band-averaged cross sections [assuming n(He I)/n(H I) = 0.1] for interstellar absorption are (for the Wisconsin energy bands) 0.8×10^{-20} cm^2 H I^{-1} for C band, 1.7×10^{-20} cm^2 H I^{-1} for B band (McCammon *et al.* 1983), and 10×10^{-20} cm^2 H I^{-1} for Be band (Bloch *et al.* 1986); the galactic H I column densities range from 0.5×10^{20} H I cm^{-2} (Lockman, Jahoda, and McCammon 1986) in some high-latitude directions to more than 10^{22} H I cm^{-2} in the galactic plane; and most of the significant column density structure in the high-latitude H I distribution is already resolved at $\sim$5° (Jahoda *et al.* 1985; Jahoda, McCammon, and Lockman 1986; Lockman, Jahoda, and McCammon 1986); the galactic ionized hydrogen column density of greater than 10^{20} H$^+$ cm^{-2} at high latitudes (Reynolds 1989) suggests that there may be additional absorption for X-rays of distant origin equivalent to $\sim 1 \times 10^{20}$ H I cm^{-2} arising from the associated He atoms.

The distribution of soft X-ray emission in the solar neighborhood has generally been modeled in terms of three source components:

1. Emission from beyond all the galactic H I, i.e., a coronal component (Bowyer, Field, and Mack 1968; Bunner *et al.* 1969; Marshall and Clark 1984);
2. Emission intermixed among the H I clouds of the galactic disk, but possibly with a different z-distribution (Davidsen *et al.* 1972; Burstein *et al.* 1977; Fried *et al.* 1980; Jakobsen and Kahn 1986; Kahn and Jakobsen 1988);
3. Emission from an entirely local component distributed within a large local H I cavity (Cox 1977; Sanders *et al.* 1977; Tanaka and Bleeker 1977; Cox and Anderson 1982; Innes and

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Hartquist 1984; Cox and Snowden 1986; Arnaud and Rothenflug 1986; Snowden 1986).

Owing to the short mean free path of soft X-rays, the radiation observed in the galactic plane must originate relatively nearby in the disk. Thus, models using primarily the coronal component require the addition of a local emission term to provide flux in the plane. This combination is the longest lived variant of the original view (absorption of an extragalactic flux). Its strength is that it can reproduce a global negative correlation of soft X-ray intensity versus $N_{\rm H\,I}$. Its weaknesses are several: the magnitude of the inferred absorption is still less than expected from known absorption cross sections; it cannot account for the large scatter seen in the correlation or for the lack of correlation toward some galactic $N_{\rm H\,I}$ features; and it predicts correlation of soft X-ray color (band ratios) with $N_{\rm H\,I}$ (analogous to interstellar reddening) where none is seen. Clumping of the H I could reduce the effective absorption cross section to that needed by the model and also produce the energy independence of the correlation, but H I studies over all conceivably relevant angular scales have shown that the necessary clumping is not present in the galactic H I (Dickey, Salpeter, and Terzian 1978; Jahoda *et al.* 1985; Jahoda, McCammon, and Lockman 1986; Lockman, Jahoda, and McCammon 1986).

A strength of models invoking the second (intermixed) component is that intermixture reduces the predicted magnitude of absorption (Burstein *et al.* 1977; Fried *et al.* 1980; Jakobsen and Kahn 1986). Other benefits depend on the specific choice of parameters, but intermixed emission models have been unable to reproduce all the major features of the data with a single set of parameters (Kahn and Jakobsen 1988; Burrows 1989). Choosing an appropriate ratio of scale heights for emission and absorption yields a plane-to-pole variation of the X-ray intensity that is a crude approximation to the X-ray versus $N_{\rm H\,I}$ correlation (Jakobsen and Kahn 1986); however, the absorbing H I must also be clumped to a greater degree than is observationally acceptable. Continuing the intermixture of emitters and absorbers at constant ratio to high optical depth can produce a saturated spectrum which is independent of variations in $N_{\rm H\,I}$ (Davidsen *et al.* 1972; Fried *et al.* 1980; Kahn and Jakobsen 1988), but in this limit there is no obvious way to produce the large intensity variations observed in different directions.

Models invoking primarily the third (local) component must provide the soft X-ray versus $N_{\rm H\,I}$ negative correlation somehow. As previously pointed out, a local X-ray emitting region filling an anisotropic H I cavity of suitable size and shape leads directly to the required negative correlation (Cox 1977; Sanders *et al.* 1977; Tanaka and Bleeker 1977). As we show below, this assignment of the relationship to a competition for space, generally referred to as displacement, provides a SXRB versus $N_{\rm H\,I}$ negative correlation which fits the observations at least as well as any of the absorption models and results in reasonable values for ISM parameters. The magnitude of the correlation is unrelated to atomic absorption cross sections and is naturally expected to be independent of X-ray energy. Scatter in the soft X-ray versus $N_{\rm H\,I}$ correlation is expected because H I structures completely outside the cavity have no influence on the observed X-ray flux. Any deviations from a simple plane-parallel distribution for the galactic H I will, in general, produce scatter in the correlation. In short, the displacement picture seems to reproduce all the observed behavior in the three soft X-ray bands simultaneously.

The true situation is observed to be more complex than any simple picture (Cox and Reynolds 1987). In some directions, the H I cavity apparently contains significant path lengths of warm H II as well as the X-ray emitting gas (e.g., toward β CMa: Gry, York, and Vidal-Madjar 1985), while in other directions (particularly toward Loop I) there is a dense H I boundary to the local cavity with X-ray emitting gas beyond, and clear signs of absorption by the intervening H I (Hayakawa *et al.* 1977; Morrison 1979; Iwan 1980). Also contrary to the simplest view, there are small amounts of neutral material within the local cavity (Bertaux *et al.* 1985; Frisch and York 1983; Paresce 1984; Lallement, Vidal-Madjar, and Ferlet 1986; Paerels *et al.* 1986). The goal of this paper, however, is to explore a very simple version of the displacement model and to examine in detail the extent to which it can accommodate the major features of the data.

In § II, we discuss the local cavity in the galactic H I as revealed by interstellar absorption line studies and by 21 cm measurements. In § III, we describe a simple displacement model, calculate the relationship between galactic H I and SXRB intensity that it predicts, and compare that to the measured data. In § IV, we present in some detail the geometry and parameters of the resulting best fit. Further discussion and conclusions are contained in §§ V and VI.

Before proceeding to discuss the displacement model, it is useful to inquire why the two other pictures have seemed attractive. The answer is very likely that, like the extragalactic model, they correspond to widely held views of what things ought to be like. It is a fairly common presumption that the Galaxy should have an X-ray emitting corona, although there have been no positive detections of such coronas in several other spiral galaxies that have been examined (Bregman and Glassgold 1982; McCammon and Sanders 1984; Cox and McCammon 1986). Similarly, there is a perception that the interstellar medium has a pervasive hot component within which are embedded the H I clouds, although direct evidence that there is an extensive X-ray–emitting interstellar phase is lacking. The most widely accepted ISM model of this sort (McKee and Ostriker 1977) has a hot phase that is typically too cold to generate the X-rays in question and resorts to a hotter local bubble to achieve the observed soft X-ray background.

II. EXISTENCE OF A LOCAL CAVITY IN THE GALACTIC NEUTRAL HYDROGEN

That there is a local deficiency in H I relative to the galactic average is well established by ISM UV absorption-line studies with the *Copernicus* and *IUE* satellites. Direct Lα measurements of H I column density show negligible amounts of neutral material (less than 5×10^{18} H I cm^{-2}) out to distances as great as 200 pc (e.g., toward β CMa: Bohlin, Savage, and Drake 1978). The studies of Frisch and York (1983) and Paresce (1984) attempted to quantify these results in terms of the shape and extent of the local cavity.

This local deficiency can also be seen in the 21 cm measurements of total H I column density (Knapp 1975; Lockman 1986). Bloemen (1987) published a distribution function for the z-dependence of the mean neutral hydrogen density for the Galaxy. This function has two components: a Gaussian component (135 pc scale height and midplane density of 0.37 H I cm^{-3}) which represents the gas of the galactic disk and an exponential component (400 pc scale height and midplane density of 0.10 H I cm^{-3}) which represents the diffuse material

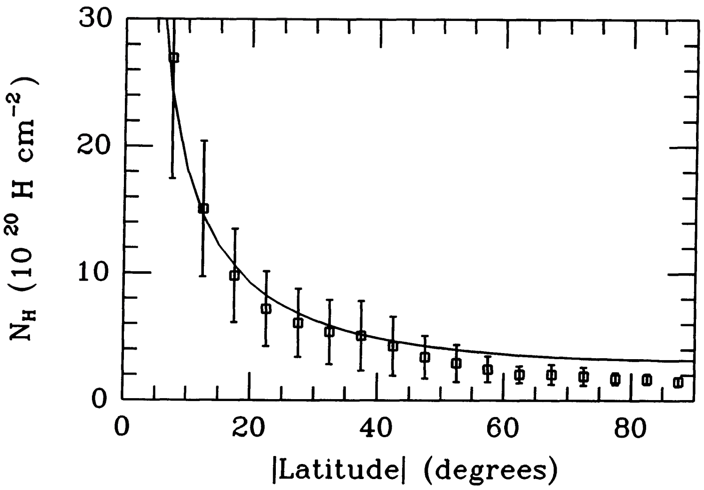

FIG. 1.—Column density of H I for 5° annuli in galactic latitude. Data are from Stark *et al.* (1990), with the northern and southern hemispheres averaged together. Vertical bars indicate the range observed at each latitude. Model curve shows the expected column density using the H I density function of Bloemen (1987).

at large distances from the galactic plane (Lockman 1986). The points in Figure 1 show the average column density of H I (Stark *et al.* 1990) for 5° annuli in galactic latitude (northern and southern hemispheres averaged together), while the curve shows the values predicted by Bloemen's H I density function. The vertical bars indicate the range of column density in each annulus. The function is reasonable for the Galaxy as a whole, as indicated by the distribution for $|b|$ less than 45°. But for higher galactic latitudes, there is a significant deficit of H I relative to the plane-parallel distribution. Given the irregular appearance of the H I distribution on the sky, one should expect a poor fit to a plane-parallel distribution wherever the line of sight samples only small distances. What is apparent from Figure 1, however, is the consistent sense of this discrepancy indicating that the local density is much lower than average.

We will refer to this region of low density as a cavity, as though it were a bounded entity. Looking at the same data, however, one could as well conclude that the solar system finds itself in a hot low-density intercloud component of the general ISM, with the local absence of H I having only to do with chance avoidance. If H I were absent from most interstellar regions and organized on the ~ 100 pc scale found for the local cavity, our own location would then be in a fairly typical environment rather than within an isolated cavity. As discussed by Cox and Reynolds (1987), the question of whether we are surrounded by a real cavity within a higher density intercloud medium, or merely by a low-density intercloud medium typical of most of the galactic disk, cannot be answered from knowing only the local condition.

III. A SIMPLE DISPLACEMENT MODEL FOR THE SXRB

The finite flux of diffuse soft X-rays ($E \leq 0.284$ keV) observed in all directions in the galactic plane coupled with the short mean free path of X-rays of this energy ($N_{\rm H\,I} \sim 10^{20}$ H I cm^{-2}) indicates that the Sun is surrounded by nearby hot ($T \sim 10^{6.0}$ K) plasma with little intervening neutral material. The results of Bloch *et al.* (1986), Bloch (1988), and Juda (1988) showing the tight correlation between the Be band (0.078–0.111 keV) and B band (0.13–0.188 keV) count rates make this requirement even stronger, since one optical depth in the Be band is only 10^{19} H I cm^{-2}, about 6 times smaller than in the B band. Given these observations, it is a plausible assumption that the hot plasma occupies the cavity of § II.

We will now consider the simplest possible model for the $\frac{1}{4}$ keV diffuse background—or at least the one with the fewest free parameters. We will assume that this hot plasma in the cavity is the source of *all* the observed $\frac{1}{4}$ keV background, that the X-ray emissivity of the plasma is uniform, and that it fills the entire cavity in the H I. The intensity of the SXRB in a given direction is then equal to the product of the path length from the Sun to the edge of the cavity multiplied by the emissivity of the plasma, or $I = \epsilon D$, where I is the observed SXRB intensity, ϵ is the constant emissivity of the plasma, and D is the distance from the Sun to the edge of the cavity. If the plasma pressure is not to greatly exceed the average interstellar pressure, the X-ray emission volume must have a spatial extent on the order of the thickness of the galactic disk. In those directions where the X-ray intensity is higher, it must extend further, excluding more of the neutral phase of the ISM, leading to a negative correlation between the intensity of the SXRB and the column density of neutral hydrogen. This is the basis of the model presented by Sanders *et al.* (1977) and upon which we elaborate in this paper. The real situation is obviously more complicated, but we will show that this zero-order model fits the data at least as well as any other that has been proposed and that the derived parameters are entirely consistent with what we currently know about the ISM.

Using the Bloemen model of the z-distribution of H I noted above and the geometry of the cavity determined from the intensity of the SXRB, we calculate the expected residual column density of H I in each direction. We assume that the cavity exists in a region in which the neutral gas was originally smoothly distributed with the average galactic H I parameters. We then compare the expected residual column densities with the observed values.

For this analysis, we use the Wisconsin survey B band data (McCammon *et al.* 1983) for the determination of the cavity geometry and the H I column densities from Stark *et al.* (1990). Excluded from this analysis are regions where the X-ray data are suspected to be contaminated (Burrows 1982; McCammon *et al.* 1983), where the X-ray data are seriously affected by point sources (e.g., HZ 43), and regions of enhanced extended diffuse X-ray emission that are not associated with the general diffuse background (e.g., the North Polar Spur). We also exclude data where the measured column density of H I is greater than 10^{21} H I cm^{-2}, so that only reasonably local structure is sampled rather than distant material in the galactic plane. The high–column-density bulge in the southern hemisphere toward the direction of the galactic anticenter (much of which is included in the analysis), where $N_{\rm H\,I}$ is as high as 7×10^{20} H I cm^{-2} as far south as $b = -40°$, is an obvious example of departure from a plane-parallel distribution for the H I and is a direction in which the simple model described here fails. The data are binned into pixels of 117 square degrees (typically 10°.8 × 10°.8), the centroids of which are shown in Figure 2.

If the cavity were formed by simply removing material, the expected column density of neutral hydrogen external to the

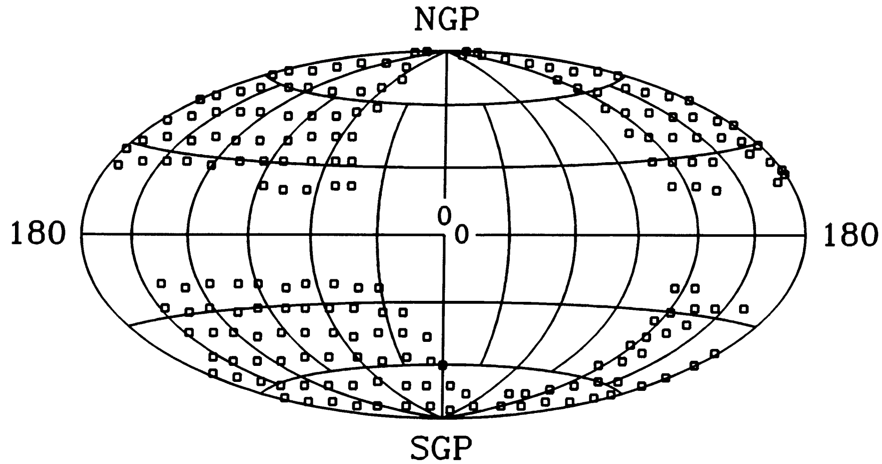

FIG. 2.—Aitoff projection in galactic coordinates (centered on $l = 0°$, $b = 0°$) showing the pixel centroids for the B band data used in this analysis

cavity would be given by the equation

$$N^E_{\rm H\,I} = \int_D^\infty n(r)dr$$
$$= \int_D^\infty 0.37 \exp\,[-0.5(r \sin b + z_0)^2/135^2]dr$$
$$+ \int_D^\infty 0.10 \exp\,[-(|r \sin b + z_0|)/400]dr\ ,$$

where z_0 is the distance from the Sun to the galactic midplane. If the material were swept to the edge of the cavity from the interior along the line of sight from the Sun, then the residual column density due to this material would be given by the equation

$$N^I_{\rm H\,I} = (1/D^2) \int_0^D r^2 n(r)dr$$
$$= (1/D^2) \int_0^D 0.37 r^2 \exp\,[-0.5(r \sin b + z_0)^2/135^2]dr$$
$$+ (1/D^2) \int_0^D 0.10 r^2 \exp\,[-(|r \sin b + z_0|)/400]dr\ .$$

Errors in the calculation of $N^I_{\rm H\,I}$ if the Sun is not at the center of the radial displacement are reasonably minor. If the material is swept up radially from a center displaced from the Sun by a distance R, the error in a given direction is roughly 1.45×10^{18} $R \cos\theta$ H I cm^{-2}, where θ is the angle between the Sun-center line and the given direction (assuming a constant original H I space density of 0.47 H I cm^{-3}). The maximum error if the center is displaced by 35 pc (for example) is then 5×10^{19} H I cm^{-2}. This is reassuring since it eliminates the requirement that the Sun be at the center of the expansion (i.e., at the location of the supernovae, OB association, or other cause of the cavity). A full calculation of the swept-out column density including nonradial displacement, such as when a shock is deviated by running into a denser cloud, is beyond the scope of our simple model.

Figure 3*a* shows a scatter plot of the predicted column density of H I, $N^P_{\rm H\,I}$, versus the observed column density of H I for a cavity with the material simply removed ($N^P_{\rm H\,I} = N^E_{\rm H\,I}$). The best fit is determined by minimizing the root mean square residual (RMSR) when varying the assumed X-ray emissivity of the plasma and the assumed offset of the Sun from the galactic plane (ϵ and z_0 are varied). The best-fit X-ray emissivity of the gas is 0.48 B band counts s^{-1} pc^{-1}. Since the observed C/B/Be band ratios require a temperature near $10^{6.0}$ K, this implies a pressure of about 9000 cm^{-3} K for an equilibrium plasma with normal abundances (equilibrium spectra from Raymond and Smith 1977 and Raymond 1988). This is consistent with the total pressure expected in the galactic plane, as discussed in § IV. If we assume instead that material was swept out to form a shell at the edge of the emission region, then the total H I column density is $N^P_{\rm H\,I} = N^E_{\rm H\,I} + N^I_{\rm H\,I}$. This requires about a 60% larger cavity and reduces the implied X-ray emissivity of the gas to 0.30 B band counts s^{-1} pc^{-1}. The resulting scatter plot is almost identical to Figure 3*a*, showing an insensitivity to the exact mechanics of cavity formation. The assumed offset of the Sun has little effect on the best-fit emissivity of the plasma and only slightly affects the RMSR (for $0 < z_0 < 30$ pc). The best fit in either case is achieved with a positive (northerly) offset of 16 pc. This is consistent with the stellar results of Blaauw (1960) and the more recent high-latitude molecular cloud results of Magnani, Blitz, and Mundy (1985).

For comparison, Figure 3*b* shows the Bloemen model versus the observed column density of neutral hydrogen if there were no cavity. The best fit, varying only z_0, is achieved with a solar offset of 22 pc. As expected from § II and Figure 1, the agreement is reasonably good only at higher column densities (lower latitudes, where more of the galaxy is sampled). At lower column densities (higher latitudes), the model column densities are larger than those observed indicating a local deficit of H I. In essence, this is just revisiting the results shown in Figure 1. The points below the line in Figure 3*b* are from directions where the model column densities are smaller than those observed. In these directions of H I excess, the simple displacement model *must* fit poorly: the maximum values for $N^P_{\rm H\,I}$ are achieved in the no-cavity case.

To compare the quality of the displacement model fit with the negative correlation predicted by absorption, we now perform a similar analysis using a simple two-component model. Figure 4 shows the observed B band SXRB intensity versus the observed neutral hydrogen column density. The curve is the best fit of the two-component isotropic-source absorption model ($I = I_0 + I_1 e^{-\sigma N_{\rm H\,I}}$) to the data in which I_0, I_1, and σ have been allowed to vary. The best-fit magnitude of

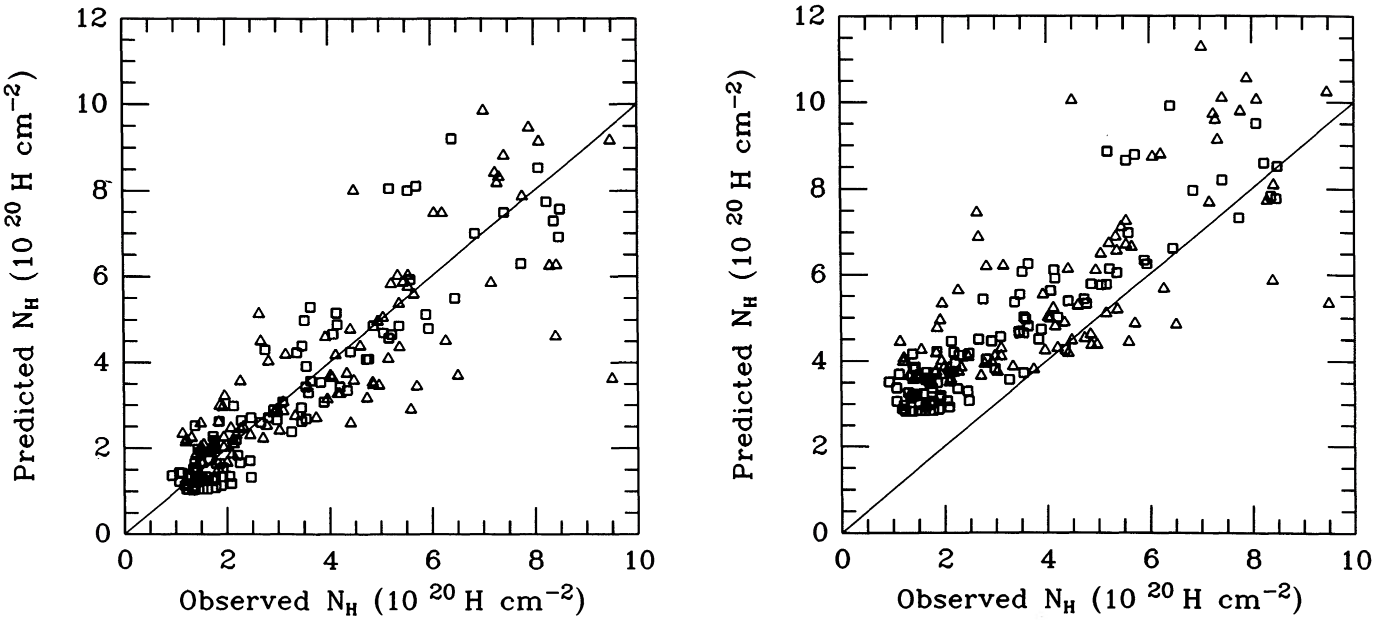

FIG. 3a FIG. 3b

FIG. 3.—(*a*) Scatter plot of predicted vs. observed neutral hydrogen column density for the situation where the material was simply removed during cavity formation. The plasma emissivity is 0.48 counts s^{-1} pc^{-1}. Squares indicate northern hemisphere data, while triangles indicate southern hemisphere data. (*b*) Same as (*a*), except that no cavity is assumed.

I_0, the local (unabsorbed) intensity, 38.7 counts s^{-1}, corresponds to a plasma emission measure of 0.0018 cm^{-6} pc (assuming an equilibrium source plasma of $10^{6.0}$ K). The best-fit magnitude of I_1, the distant (absorbed) intensity, 109.7 counts s^{-1}, corresponds to a plasma emission measure of 0.0051 cm^{-6} pc, again assuming a $10^{6.0}$ K equilibrium plasma. (The emission measures were calculated using the equilibrium plasma model of Raymond and Smith 1977 and Raymond 1988.) The effective cross section for absorption, σ, for this best fit is 0.76×10^{-20} cm^2 H I^{-1}. This value is less than half the calculated value given in § I, and the discrepancy is very difficult to explain. The figure shows a reasonable fit to the general negative correlation between the SXRB and the column density of neutral hydrogen. It is the reasonableness of this fit that has provided the bulk of the evidence in favor of the role of absorption in generating the negative correlation between the SXRB and $N_{\rm H\,I}$. The fact that the best-fit cross section is at all close to the calculated value, coupled with the idea that H I clumping could bring them into agreement, has been taken as strong evidence that absorption must be involved in spite of the strong observational evidence against the required clumping. The realization that the displacement model, without any clumping, easily provides a very similar negative correlation of SXRB with $N_{\rm H\,I}$ makes the two-component absorption model

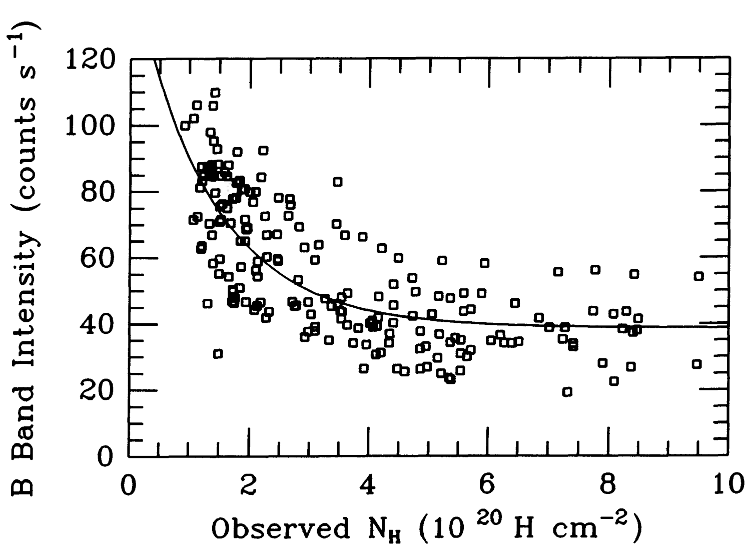

FIG. 4.—Scatter plot of B band SXRB intensity vs. the total neutral hydrogen column density with a fitted two-component absorption model curve

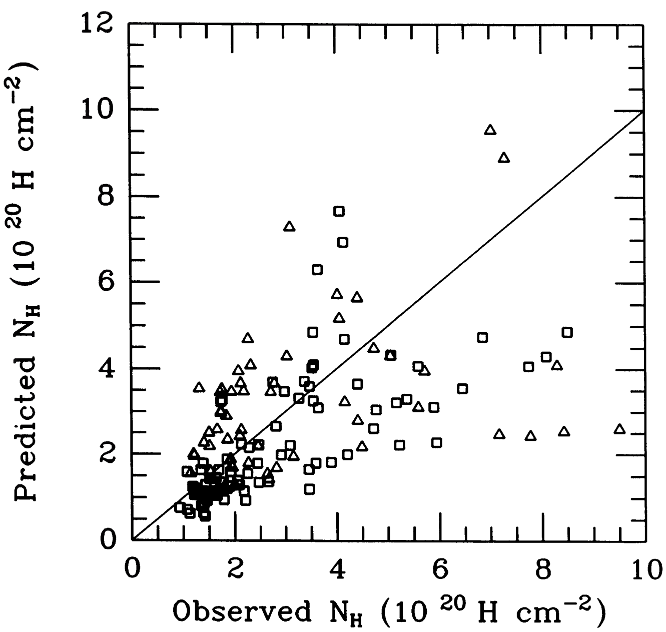

FIG. 5.—Scatter plot of the column density of neutral hydrogen predicted by the absorption model fit vs. the observed neutral hydrogen column density. This can be compared directly with Fig. 3*a* for the displacement model.

much less attractive. It is an unfortunate coincidence that the introduction of neutral gas at the average interstellar density into a region decreases the SXRB intensity by a similar amount, whether by absorbing a more distant component or by displacing a closer component at $10^{6.0}$ K and reasonable interstellar pressure.

Figure 5 shows the column density of neutral hydrogen predicted from the B band SXRB intensity versus the observed column density of neutral hydrogen by inverting the absorption model relation, $N^P_{\rm H\,I} = 1/\sigma \ln [(I - I_0)/I_1]$. Although this is the result of a three-parameter fit, the agreement is worse than that shown in Figure 3*a*, which results from the variation of only one significant parameter: the X-ray emissivity of the plasma (or equivalently, the thermal pressure). Relaxation of the isotropy of the local component, I_0, could improve the agreement considerably, but almost all the counts then come from I_0, and the model becomes a slightly contaminated displacement picture.

We have examined the predictions of both the displacement model and the two-component absorption model for $N_{\rm H\,I}$ as a function of SXRB in constant-latitude bands, where the negative correlation is still present. Our general sense is that for $|b| > 60°$, the displacement model is a better fit. For $40° < |b| < 60°$, the absorption model looks better until a group of high $N_{\rm H\,I}$ points associated with a prominent H I feature in the southern hemisphere, in the general direction of the galactic anticenter, is removed. Many of these are below the line in Figure 3*b*, corresponding to directions for which the simple displacement model, as noted, must fail. Then between $30° < |b| < 40°$, the displacement model again is a marginally better representation. At low latitudes, both models fit poorly.

There is, however, a fairly consistent trend in the way in which this displacement model fails to represent the data. The observed column densities are somewhat too high at low SXRB intensity and too low at high SXRB intensity. The model fits the latitude average correlation but provides a somewhat flatter negative correlation at constant latitude. This could be due to using an inappropriate local H I distribution with *z* (the wrong local densities or scale heights) or to an actual negative correlation between cavity extent and line-of-sight mean density. It is easy to envision a causal relationship of the latter form if the local material distribution has not altered drastically since formation of the cavity: it is not unreasonable that the cavity expanded farthest in directions of lower H I space density. If the low space density trend then continues beyond the present boundary of the cavity, there will be a lower than predicted column density of residual H I.

IV. GEOMETRY AND PARAMETERS OF THE CAVITY

Using the scale factor ϵ between SXRB intensity and distance to the cavity wall, a three-dimensional picture of the cavity configuration can be made. It is simply a scaled polar plot of the SXRB brightness distribution, similar to those of Hayakawa *et al.* (1978). These polar plots are shown in Figure 6. Each panel shows a cut along a great circle passing through the galactic poles following the indicated longitude. Figure 7 shows a cut at zero galactic latitude. The solid curves show the inferred dimensions of the cavity using the B band X-ray emissivity of 0.30 counts s^{-1} pc^{-1}. The long-dashed curves show the inferred cavity dimensions using the X-ray emissivity of 0.48 counts s^{-1} pc^{-1}. The larger cavity corresponds to models in which material has been swept to the cavity edge rather than having been removed. In Figure 6, the scale is shown by the

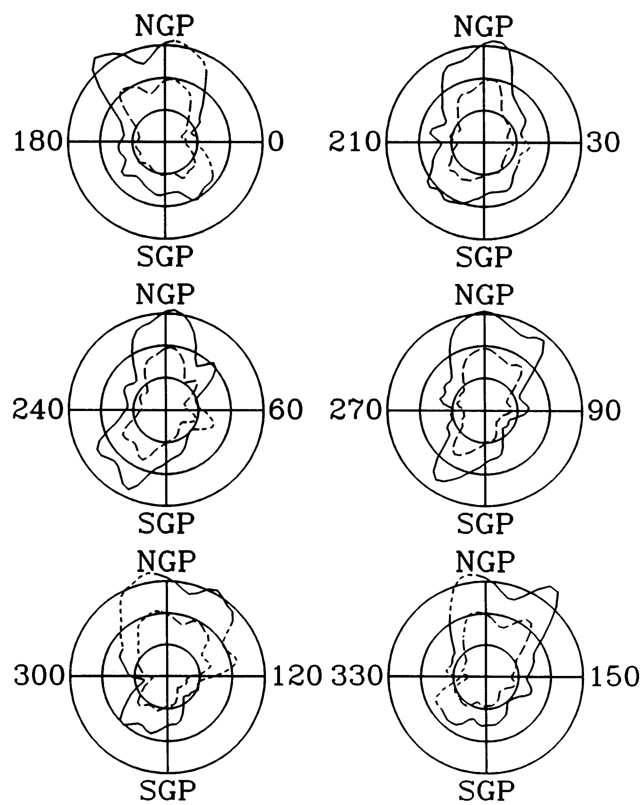

FIG. 6.—Cuts of the predicted X-ray emission volume through the north and south galactic poles along the labeled longitudes. Solid curves are derived using the SXRB intensity to distance relation $D = I/0.30$ pc. Long-dashed curves are derived using the relation $D = I/0.48$ pc. The three scale circles have radii of 100, 200, and 300 pc. Short-dashed curves indicate regions affected by point or extended sources, contamination, or poor coverage.

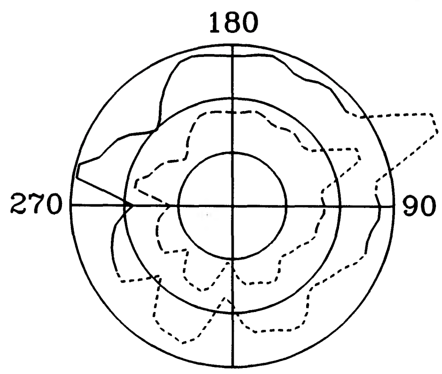

FIG. 7.—Same as Fig. 6 except that the cut is through the emission volume at zero galactic latitude. The three scale circles have radii of 50, 100, and 150 pc.

three circles with 100, 200, and 300 pc radii. In Figure 7, the circle radii are 50, 100, and 150 pc. These plots include directions with emission from known point or extended sources and data with non–X-ray contamination. This excess emission can increase the inferred cavity radius in certain directions (e.g., the North Polar Spur). These directions are indicated by short-dash curves that can be taken as upper limits to the extent of the local hot gas. Regions of poor spatial coverage are also short dashed.

As noted in Cox and Snowden (1986), the inferred cavity is far from spherical. It is much more extended away from the galactic plane with a striking asymmetry between the northern and southern galactic hemispheres. This distended shape is in qualitative accord with the probable shape of a cavity excavated by supernovae or the stellar winds of an OB association (although there is no apparent remnant of such an association in the cavity), an interpretation which is also consistent with the discrepancies between the simple model and the H I data, as alluded to in the previous section. Material is swept out preferentially in directions of lower density and thus in general out of the plane of the Galaxy, but also following density variations at constant latitude.

Table 1 lists parameters for the emission volume for the two plasma emissivities of § III. For an equilibrium plasma at $10^{6.0}$ K and plasma emissivity of 0.48 counts s^{-1} pc^{-1}, the mean square electron density is 2.2×10^{-5} cm^{-6}. The electron density is then 0.0047 cm^{-3}, which yields a thermal gas pressure (p/k) of 9000 cm^{-3} K. Thermal pressures of this magnitude for the plasma exceed the thermal pressure inferred for the partly ionized very local interstellar medium ($p/k \sim 2600$ cm^{-3} K: Bertaux *et al.* 1985), but are $\leq 50\%$ of the total pressure determined for the ISM by hydrostatic modeling of the z-distribution of galactic material ($p/k > 2 \times 10^4$ cm^{-3} K: Badhwar and Stevens 1977; Bloemen 1987; Spitzer 1990; Boulares and Cox 1990). The difference in thermal pressures can easily be borne by a magnetic contribution to the pressure of the local cloudlet. It is probable that the interstellar magnetic field (and therefore magnetic pressure) is lower within the cavity and the thermal pressure correspondingly higher (Cox and Snowden 1986; Cox and Reynolds 1987). With the above parameters and the equilibrium plasma model of Raymond and Smith (1977) and Raymond (1988), there is an O VI spatial density of 1.4×10^{-8} cm^{-3} and a column density of 4.2×10^{12} cm^{-2} for a typical 100 pc path length through the cavity. The maximum O VI column density in the cavity is then $\sim 10^{13}$ cm^{-2}, neglecting any contribution from conduction boundaries with embedded cloudlets or the cavity wall.

A notable aspect of the model presented here is that the state of the cavity and plasma can be indefinitely long lived (Cox and Snowden 1986). The stored energy ($\sim 10^{51}$ ergs) is of an order which can be supplied by a supernova, and the recurrence time for supernovae in a cavity of this size (a few million years) is less than or comparable to the radiative lifetime of the plasma ($\sim 10^7$ yr).

TABLE 1

PARAMETERS OF THE LOCAL EMISSION VOLUME

Quantity	Material Removed	Material Swept Out
Plasma emissivity (B band counts s^{-1} pc^{-1})	0.48	0.30
Electron density (cm^{-3})	0.0047	0.0037
Plasma temperature (K)	$10^{6.0}$	$10^{6.0}$
Thermal pressure (p/k: cm^{-3} K)	9000	7100
Mean emission volume radius (pc)	102	161
Emission volume (cm^{-3})	2.0×10^{62}	7.7×10^{62}
Radius of equivalent sphere (pc)	118	185
Emission volume surface area (cm^2)	1.4×10^{42}	3.5×10^{42}
Stored energy (ergs)	3.7×10^{50}	11.3×10^{50}
Volume luminosity (ergs s^{-1})	5.1×10^{35}	12.1×10^{35}
Radiative lifetime (yr)	2.3×10^7	3.0×10^7
O VI space density (cm^{-3})	1.4×10^{-8}	1.1×10^{-8}

V. CONSISTENCY WITH ISM ABSORPTION-LINE MEASUREMENTS

Figure 8 shows the B band SXRB intensity toward certain stars versus the stellar distance (data from Paresce 1984). Open and closed symbols indicate stars with respectively less than and greater than 6×10^{18} H I cm^{-2} of foreground interstellar material. Squares indicate stars for which the column density of foreground H I was determined by Lα measurements. Triangles indicate stars where other absorption lines were used, resulting in less precise column density determinations. Repre-

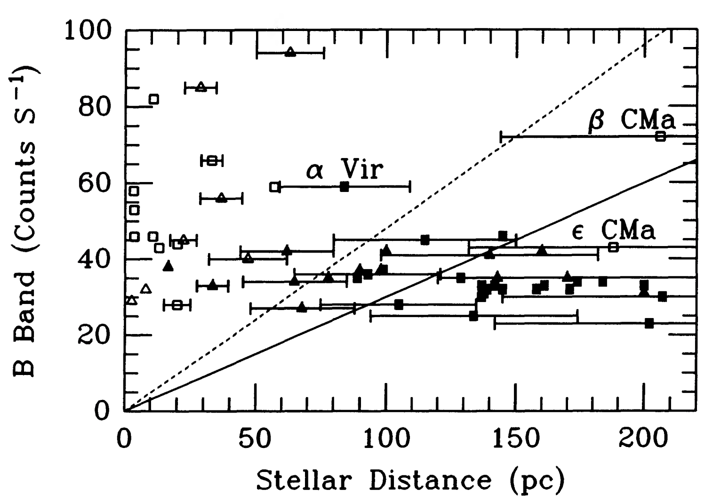

FIG. 8.—B band intensity in the direction of certain stars vs. stellar distance. Filled symbols indicate stars with foreground ISM column densities greater than 6×10^{18} H I cm^{-2}; open symbols indicate stars with less foreground material. Squares indicate stars where the H I column density was determined using Lα measurements; triangles indicate that other absorption lines were used. Solid and dashed lines show sample relations between SXRB intensity and cavity radius (plasma emissivities of 0.30 and 0.48 counts s^{-1} pc^{-1}, respectively).

sentative error bars are shown for the uncertainties in the stellar distances. Those stars showing very little absorption are inside the cavity while those showing significant ISM absorption are presumably outside of the cavity. In perfect adherence to the assumed model, a diagonal of slope ϵ (the plasma emissivity in units of counts s^{-1} pc^{-1}) through the origin should cleanly separate the open and closed symbols. The solid and dashed lines represent the plasma emissivities determined in § III for the swept-out and removed cases, respectively. Perfect adherence is clearly not present, but with the exception of a few stars (mostly those without Lα confirmation of the column density), the expected separation is present and the removed case provides a reasonably good division. Note again that this model has essentially one free parameter and that the ISM absorption line data and stellar distances are completely independent from the data used for this analysis.

Unfortunately, the data in Figure 8 cannot constrain the value for the plasma emissivity to better than perhaps a factor of 2. The discrepant star with a Lα determination of the intervening column density placing it outside of the cavity, α Vir, lies in the direction of the North Polar Spur. This is a direction where there is a significant excess of X-ray emission from beyond the local cavity. The two discrepant stars, β CMa and ϵ CMa, with Lα measurements placing them within the cavity, lie in the direction in which it is well known that the void in the galactic neutral hydrogen extends to a very great distance. In this direction, there is a significant amount of gas that is low-density and ionized, but not hot enough to be X-ray–emitting (Gry, York, and Vidal-Madjar 1985).

It should be noted that the analysis of § III does not uniquely solve for the emissivity of the plasma. The results are dependent on the assumed scale height and midplane density of the H I density distribution. If the parameters chosen for the Galaxy as a whole overestimate the initial local density of H I, the fitted cavity is too large, and the slopes of the lines in Figure 8 are underestimated. The results are also sensitive to the assumption of the large scale-height exponential component of the H I density distribution. If all the galactic H I were in the disk component (rather than being divided between the disk and halo) the fitted cavity would also be smaller. Because of this, not too much should be made of the fact that the lines in Figure 8 have slopes which are perhaps too small.

The inferred shape of the cavity applies only to the extent of the X-ray–emitting plasma. The actual cavity in the neutral hydrogen can extend well beyond the edge of the X-ray emission volume, such as in the direction toward β CMa. Diffuse clouds within the emission volume also affect the inferred shape depending on their location and column density. The Sun itself is located in a very diffuse cloud which is at least partly neutral and has a space density of roughly 0.2 cm^{-3} (Bertaux *et al.* 1985) with a total column density of no more than $\sim 2 \times 10^{18}$ H I cm^{-2} in at least one direction (toward HZ 43: Paerels *et al.* 1986; Bruhweiler and Cheng 1988).

The analysis of this paper (with the Wisconsin survey B band data) is generally insensitive to small amounts of neutral material within the cavity. Individual clouds with column densities less than a few times 10^{19} H I cm^{-2} (such as the local cloudlet) are only a fraction of the column density needed for unit optical depth for B band X-rays (0.6×10^{20} H I cm^{-2}). High column density lumps in the ISM such as high-latitude molecular clouds (Blitz, Magnani, and Mundy 1984; Magnani, Blitz, and Mundy 1985) have solid angles which, in general, are only a fraction of the survey instrument field of view ($\sim 6°$ FWHM). In either case, if such an object lies within the cavity, it will not significantly affect the observed SXRB intensity. However, if a star lies within the cavity but behind a small amount of neutral material, it may be wrongly noted as being outside of the cavity in Figure 8. Also, a sufficient filling factor of very diffuse neutral clouds would displace the plasma and require the cavity edge to be further away than assumed here. Analysis of Be/B band ratio data by Juda (1988) allows at least the small amount of neutral material known to be in the cavity from interstellar absorption measurements and solar Lα backscatter observations.

VI. CONCLUSIONS

The simple displacement picture cannot be correct in detail. A simple extrapolation of the extragalactic power law to lower energies would provide up to $\sim 10\%$ of the C band and $\sim 5\%$ of the B band at high galactic latitudes. There are certainly regions in which galactic X-ray emission is present beyond the nearest hydrogen, yielding obvious signatures of absorption in the extreme case of the North Polar Spur. There are other directions in which the H I cavity extends further than the boundary of the X-ray emission. Nevertheless, the simplest displacement model with its one free parameter manages to be consistent with the general features of all existing data. It has no difficulties with the independence of the soft X-ray spectrum with intensity, the lack of clumping in H I, the presence of emission in the plane, or the general negative correlation of SXRB intensity with $N_{\rm H\,I}$. The inferred emissivity for the cavity is consistent with that anticipated for $10^{6.0}$ K gas at a realistic interstellar pressure. There do not appear to be any insurmountable difficulties with the generation or longevity of the emission volume (Cox and Snowden 1986; Cox and Reynolds 1987). In the one area where the model has a systematic discrepancy, its weakness in the negative correlation of SXRB intensity with $N_{\rm H\,I}$ at constant latitude, the defect is in the direction one would expect for a more realistic H I distribution. That is, the cavity extends less far in directions with higher than average line-of-sight density. The observed variations in the C/B band ratio, which show no significant correlation with intensity, can be explained by small variations in the average temperature in different directions.

The only peculiarity of the model that remains is that in Figure 7 the Sun is found a little too well centered in the zero galactic latitude cut. From Figure 6, however, it is clear that this special location is peculiar to that particular cut.

On the whole, the model works at least as well as can be expected. The cavity configuration of Figures 6 and 7 cannot be precisely correct, and reality must include some admixture of absorption and embedded clouds, but it is difficult to envision that the bulk of the observed X-rays do not come from a low-density region of similar extent to the cavity derived here. The questions of the nature of the cavity boundary and the ubiquity of 10^6 K gas in the galactic disk remain unanswered, but this simplified model provides a useful framework within which they can be addressed.

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