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LIMITS ON THE DENSITY OF NEUTRAL GAS WITHIN 100 PARSECS FROM OBSERVATIONS OF THE SOFT X-RAY BACKGROUND

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ABSTRACT

We present observations in two soft X-ray bands, the Be band (0.077–0.111 keV) and the B′ band (0.105–0.188 keV), for nine directions in the sky. The ratio of count rates in these two bands remains constant as the rates vary by a factor of 3, even though the effective interstellar absorption cross sections in the bands differ by a factor of ~ 3.5. For a model in which the bulk of the observed soft X-ray emission originates in a uniform low-density region surrounding the Sun, the constant ratio between the band rates places an upper limit on the amount of neutral material that can be homogeneously mixed with the X-ray–emitting gas. The 2 σ upper limit on the H I column density over an average path through the local emitting region is 6.6×10^{18} cm^{-2}. If the average path length is ~ 100 pc, then clouds similar to the one in which the Sun is embedded ($n_H \sim 0.1$ cm^{-3}) could still have a filling factor as large as 25%.

Subject headings: interstellar: matter — X-rays: general

I. INTRODUCTION

Since X-rays with energies below 0.3 keV have mean free paths less than 100 pc for an average interstellar density of ~ 1 cm^{-3}, the observation of a finite X-ray intensity in the galactic plane requires that all models for the origin of the soft X-ray diffuse background include a nearby X-ray–emitting region. An obvious possibility is then for this region to produce essentially all of the observed soft X-rays (Kraushaar 1976; Sanders *et al.* 1977; Fried *et al.* 1980). Recently Snowden *et al.* (1990) have examined a simple model of this type. In their model they assume all the observed soft X-ray emission is produced in a uniform, isothermal plasma that occupies a cavity in the neutral interstellar medium surrounding the Sun. The ratio of count rates in the C and B bands implies a plasma temperature of $\sim 10^6$ K. The X-ray intensity in a given direction depends only on the path length through the emitting region in that direction: $I_B(l, b) = \alpha R(l, b)$, where I_B is the B band intensity and R is the path length. The proportionality factor, α, is determined by assuming that there is no H I within the cavity and that the H I outside the cavity follows the galactic average plane-parallel distribution given by Bloemen (1987). Its value was adjusted to get a best fit to the observed H I column density as a function of direction. The size of the cavity implied by this fit, $\langle R \rangle \approx 102$ pc, results in a reasonable pressure in the X-ray–emitting gas: $p/k \approx 9000$ cm^{-3} K. This simple model is consistent with existing UV interstellar absorption observations that show a low density of neutral gas within ~ 100 pc of the Sun, and it explains the observed energy-independent anticorrelation of X-ray intensity and H I column density in a straightforward way.

The Snowden *et al.* (1990) model assumes that there is no absorbing material within the X-ray–emitting region. However, observations of backscattered solar radiation indicate that the Sun is itself embedded in neutral gas (Bertaux 1984, and references therein), and interstellar absorption measurements toward stars within ~ 100 pc provide evidence for column densities of a few times 10^{18} H I cm^{-2} within the X-ray–emitting volume (McClintock *et al.* 1978; Gry, York, and Vidal-Madjar 1985; Murthy *et al.* 1987; Frisch and York 1983; Paresce 1984). We would like to know whether this simple model for the origin of the soft X-ray background is consistent with the amount of absorbing material known to be within the X-ray emitting region. The analysis presented in this paper is an attempt to determine an upper limit on embedded absorbing material in the context of the Snowden *et al.* (1990) local emission model and does not address the question of whether some other model for the origin of the X-rays might be correct (see, for example, Marshall and Clark 1984; Kahn and Jakobsen 1988; Bochkarev 1987; however, see also McCammon *et al.* 1983; Burrows 1989; McCammon and Sanders 1990).

II. EXPERIMENT

The data presented here are from NASA sounding rocket flight 27.103UH, launched from White Sands Missile Range, New Mexico on 1986 February 1 at 0540 UT. The flight reached a peak altitude of 227 km at 246 s after launch. This was the second flight of the instrument described by Bloch *et al.* (1986). The experiment pointed at nine selected positions on the sky for about 12 s each. The positions were chosen to cover a large range of soft X-ray count rates, as determined by the B band of the Wisconsin sky survey (McCammon *et al.* 1983).

The observations were made using two wire-wall proportional counters with five-sided anticoincidence and $\sim 15° \times 15°$ (FWHM) mechanical collimation. Beryllium and boron K-edge absorption filters in combination with pulse-height selection defined broad energy bands in the two counters: the Be band (0.077–0.111 keV) and the B′ band (0.105–0.188 keV). Figure 1 is a plot of the throughput in each band as a function of energy. The boron-filtered band is referred to here as B′ to distinguish it from the Wisconsin sky survey B band, which had a thicker window and therefore relatively less response at lower energies. Counter gains were measured periodically during the flight by exposing each of the counters to a source of 1.25 keV X-rays.

The charged particle background was less than 0.5 counts s^{-1} for each band, and atmospheric transmissions exceeded 90% in the B′ band for all the pointed directions and in the Be band for all but the first and last. There is an error of at most 5% in the corrected rates due to uncertainties in the X-ray

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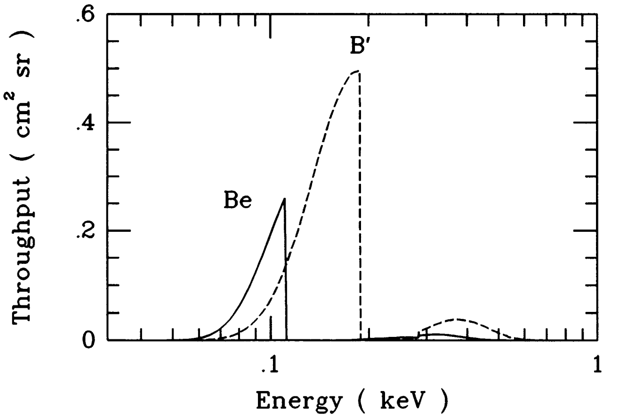

FIG. 1.—Effective area-solid angle product as a function of photon energy for the Be and B′ bands.

emission spectrum and atmospheric model parameters. The centers of the observed fields and the corrected count rates in the Be and B′ bands are listed in Table 1.

III. ANALYSIS

Figure 2 is a plot of the Be band rate against the B′ band rate for the nine fields on the sky of Flight 27.103. The best-fit ratio of Be band to B′ band count rates is 0.567 ± 0.079 (3 σ confidence) with $\chi^2 = 2.77$ for 8 degrees of freedom. The predicted Be/B′ band rate ratio is quite insensitive to temperature for gas near 10^6 K, and the observed ratio is consistent with unabsorbed emission from a thermal equilibrium plasma (Raymond and Smith 1987) at any temperature in the rather broad range of $10^{5.8} \leq T \leq 10^{6.2}$ K, despite its small uncertainty. This temperature range is much larger than that required to explain the observed variation in B/C ratio among these directions ($10^{5.95} < T < 10^{6.05}$ K). Bloch *et al.* (1986) reached the same conclusions by comparing Be band data from an earlier flight to B band data from the Wisconsin sky survey. We note that the first target in Table 1 is almost centered on the Gemini-Monoceros soft X-ray enhancement, which has been interpreted as a supernova remnant at a distance of ~300 pc (Nousek *et al.* 1981). It might therefore be expected to affect the Be/B′ ratio observed in this direction, but any effect appears to be small.

The Be/B′ ratio is observed to be the same in all directions, as expected in the Snowden *et al.* (1990) model. Their model has no absorbing gas in the cavity because the X-ray data do not require any. We are interested in determining whether this simple model can accommodate at least the small amounts of nearby absorbing gas known to exist, or whether they should have been apparent in the low-energy X-ray measurements.

TABLE 1

FLIGHT 27.103 Be AND B′ BAND COUNTING RATES CORRECTED FOR NON–X-RAY BACKGROUND AND ATMOSPHERIC ABSORPTION

Position (l, b)	Be Band Rate (counts s^{-1})	B′ Band Rate (counts s^{-1})
199°, +13°	5.87 ± 1.16	9.82 ± 1.27
210, +52	6.87 ± 0.82	11.99 ± 0.99
223, +66	8.04 ± 0.84	15.46 ± 1.03
179, +66	8.94 ± 0.82	16.12 ± 1.03
150, +55	10.66 ± 0.86	18.23 ± 1.11
150, +36	5.95 ± 0.60	11.39 ± 0.82
227, +7	4.06 ± 0.56	5.80 ± 0.65
166, +4	4.68 ± 0.60	7.56 ± 0.68
135, +0	4.34 ± 0.71	7.76 ± 0.81

When the emitting region contains intermixed absorbing gas, the X-ray count rate is no longer proportional to the distance to the edge of the cavity, as X-rays from the more distant sections of the emitting region are more likely to be absorbed. The Be band will be affected more than the B′ band, so we expect the Be/B′ ratio to be less in directions where the distance to the edge of the cavity is greater (i.e., directions with higher counting rates). Given a bounded region of homogeneously intermixed emitting and absorbing gas, the solution to the radiative transfer equation for the intensity, I_E, of the emission at energy E is

$$I_E = S_E(1 - e^{-\sigma_E n_\mathrm{H} d}) , \tag{1}$$

where $S_E = \Lambda_E(T) n_e^2 / 4\pi\sigma_E n_\mathrm{H}$ is the source function at energy E, $\Lambda_E(T) n_e^2$ is the volume emissivity at energy E of the hot plasma at temperature T, n_H is the intermixed neutral hydrogen density, σ_E is the absorption cross section of the neutral gas at energy E, and d is the path length through the cavity to the edge of the emitting region. If the quantities that determine the source function are constant throughout the cavity, the only quantity in equation (1) that can be varied among different lines of sight to vary the intensity is the emission path length, or equivalently, since n_H is fixed, the intermixed H I column density, $N_\mathrm{H} = n_\mathrm{H} d$.

Equation (1) can be generalized to band rates for comparison with the data by averaging the terms over energy using the band response as a weighting function. Thus we have two equations like equation (1):

$$I_{\mathrm{B}'} = S_{\mathrm{B}'}(1 - e^{-\sigma_{\mathrm{B}'} N_\mathrm{H}}) \tag{2}$$

and

$$I_\mathrm{Be} = \frac{\lambda}{\beta} S_{\mathrm{B}'}(1 - e^{-\beta\sigma_{\mathrm{B}'} N_\mathrm{H}}) , \tag{3}$$

where $S_{\mathrm{B}'}$ is the source function for the B′ band, λ is the ratio of the Be and B′ band emissivities ($\lambda \equiv \Lambda_\mathrm{Be}/\Lambda_{\mathrm{B}'}$), and β is the ratio of the Be and B′ band absorption cross sections ($\beta \equiv \sigma_\mathrm{Be}/\sigma_{\mathrm{B}'}$). The band-averaged effective cross sections depend on the

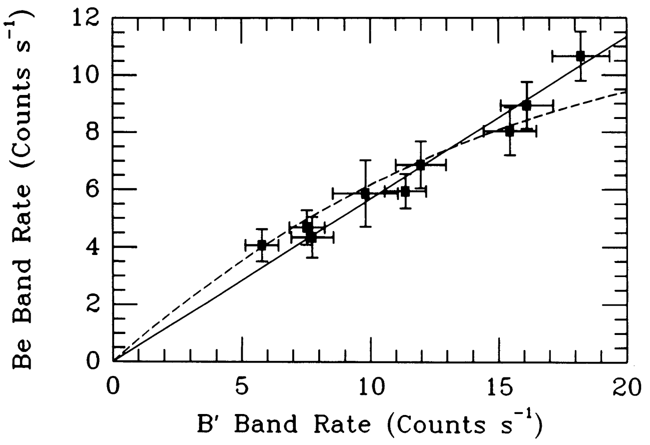

FIG. 2.—Be and B′ band rates for the nine fields observed in this experiment. The solid line is the best-fit constant ratio. The dashed curve is the relationship between the rates predicted by our 2 σ upper limit on the amount of intermixed absorbing gas.

assumed source spectrum and absorbing column density, but for plasma temperatures near 10^6 K and column densities less than $\sim 2 \times 10^{19}$ cm^{-2}, they vary by less than 10% from typical values of $\sigma_{B'} = 3.0 \times 10^{-20}$ cm^2 and $\sigma_{Be} = 10.5 \times 10^{-20}$ cm^2. We have used plasma emission spectra from Raymond and Smith (1987) with solar abundances (Allen 1973) and interstellar absorption cross sections from Morrison and McCammon (1983). The parameter λ is a function of the temperature of the emitting gas and can be adjusted to find the best fit. The most interesting parameter is $S_{B'}$, since a lower limit on it provides an upper limit on the intermixed H I column density in a given direction.

Given fixed values for β, λ, and $S_{B'}$, equations (2) and (3) give count rates in the Be and B′ bands as a function of N_H which can be compared with the observed data. For each observed field, the H I column density that minimizes the sum of the contributions of the two band rates to the χ^2 is found. The total χ^2 is then calculated by summing these minimum contributions for all nine fields. This can be repeated for a grid of values of λ and $S_{B'}$, and the values for these parameters which minimize the total χ^2 can be found.

Following this procedure with β fixed at 3.5, the best-fit values for λ and $S_{B'}$ are 0.62 and 190 counts s^{-1}, respectively. This value of λ agrees with the predicted value for thermal emission over the temperature range near 10^6 K required by the B/C ratios observed in the Wisconsin sky survey (McCammon *et al.* 1983). Equation (2) can be inverted so that for a given value of $S_{B'}$ the H I column density in a given direction can be found as a function of the B′ band rate. The 2 σ lower limit on $S_{B'}$ is 49 counts s^{-1}, which implies upper limits on the intermixed H I column densities in the observed directions of (4.2–15.5) $\times 10^{18}$ cm^{-2}. The Be versus B′ curve for this 2 σ limit is plotted in Figure 2 as a dashed curve.

We can obtain an "all-sky average" B′ band rate by scaling the 49 counts s^{-1} average B band rate from the Wisconsin sky survey by the average B′/B band rate ratio of 0.18 for the targets observed on this flight. For a direction with this typical B′ band count rate of 8.8 counts s^{-1}, the 2 σ upper limit on the intermixed H I column density would be 6.6×10^{18} cm^{-2}.

It is unphysical for the hot X-ray–emitting plasma and cool absorbing gas to be mixed atom by atom. Clearly, they must be physically separated. The scatter in the H I column densities measured toward stars inside the cavity also suggests that the neutral gas is clumped. Clumping H I gas into clouds reduces its effectiveness at absorbing X-rays. As the clouds become optically thick, the effective band absorption cross sections are reduced, and so is their ratio, β.

There are no data on the average column density for clouds within the cavity. The only cloud definitely known to exist within the cavity is the one surrounding the Sun, so we adopt its derived properties as typical. The local gas density derived from observations of solar radiation scattered by interstellar gas streaming through the solar system is ~ 0.1 cm^{-3} (Bertaux 1984). The H I column densities measured toward stars within 5 pc of the Sun increase with distance at a rate consistent with a number density of ~ 0.1 cm^{-3}, but for greater distances the column densities stop increasing in many directions. If the local cloud has a radius of 5 pc and a density of 0.1 cm^{-3}, its H I column density is 3×10^{18} cm^{-2}. A population of clouds with this H I column density would reduce the cross section ratio β only about 10% from its intrinsic value of ~ 3.5.

The clouds described above would have fairly large angular sizes (12° at 50 pc) so that an individual observation would not provide a very good sample of the random distribution of cloud locations assumed in the calculations above. However, since the optical depth of each cloud and the calculated magnitude of the clumping effect are small, fluctuations around the calculated mean value of the clumping effect are unlikely to be large compared to our statistical uncertainties. We therefore have simply repeated the previous fitting procedure using the reduced value of β. Figure 3 is a plot of $\chi^2(S_{B'}, \lambda)$ values for $\beta = 3.2$. The scale along the top edge of the plot gives the intermixed H I column density corresponding to $S_{B'}$ for an average path length through the emitting region. The 2 σ upper limit on the intermixed H I column density is 7.8×10^{18} cm^{-2}, which makes $\langle n_H \rangle \leq 0.025$ cm^{-3} for a mean cavity radius of 102 pc. If the clouds have an average density of 0.1 cm^{-3}, then the filling fraction of clouds in the cavity could still be as large as 0.25. This allows a reasonably high *a posteriori* probability for the Sun to be inside a cloud.

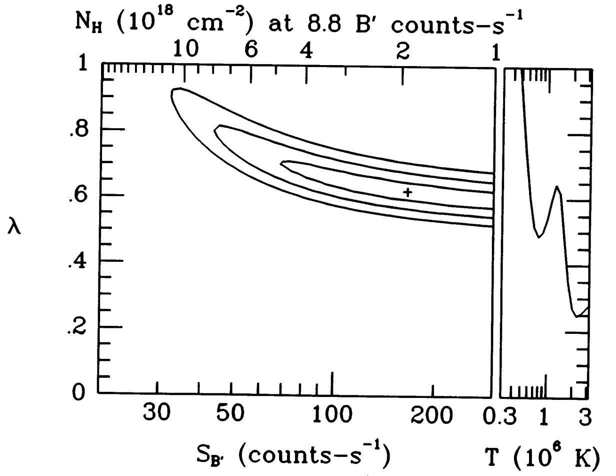

FIG. 3.—Confidence limits on the parameters $S_{B'}$ (B′ band source function) and λ (the Be/B′ emissivity ratio) for a model in which the absorbing material is intermixed with the X-ray–emitting gas in clouds of average H I column density 3×10^{18} cm^{-2}. The contours are at 1 σ, 2 σ, and 3 σ. The upper scale shows $S_{B'}$ as the total absorbing column density to the edge of the emitting region for a direction with an average soft X-ray rate. The curve to the right can be used to convert the emissivity ratio into temperature.

IV. SUMMARY

The Be/B′ band rate ratio appears to be the same for all nine directions observed on Flight 27.103 even though the lower energy Be band radiation is much more readily absorbed by interstellar material. This is the expected result if the X-rays arise in a uniform, absorption-free emitting region of variable extent surrounding the Sun. Snowden *et al.* (1990) point out that there is known to be some cool gas within their emitting volume. We have therefore analyzed these data to determine whether the X-ray data are consistent with the neutral gas known to be present, and to determine the maximum amount of absorbing material allowed in the context of this simple model. If the absorbing gas is distributed in clouds of H I that are optically thin in the Be and B′ bands, a 2 σ upper limit of 6.6×10^{18} cm^{-2} can be placed on the absorbing column density to the edge of the cavity along an average line of sight. This limit is increased to only 7.8×10^{18} cm^{-2} if the H I is clumped into clouds of average thickness 3×10^{18} cm^{-2}. Such column densities are comfortably in excess of the values observed for nearby stars, which are typically $\sim 1 \times 10^{18}$ cm^{-2}. Actual detection of such small quantities of gas in X-ray absorption would require observations at energies below 50 eV. We note, however, that the most recent flight of this instrument has found possible evidence for Be band absorption in one direction in the southern galactic hemisphere (Edwards *et al.* 1990).

It is known from solar backscattering measurements that the Sun is embedded in a cloud with $n_H \approx 0.1$ cm^{-3}. We would be uncomfortable if our X-ray model required such clouds to be so rare that it should be very unlikely to find the Sun in one. Taking the mean cavity radius of 102 pc found by Snowden *et al.* (1990) to give the best agreement between the X-ray and 21 cm measurements, our 2 σ upper limit on the average volume density becomes 0.025 cm^{-3}. If we assume this is provided entirely by clouds similar to the one surrounding the Sun, their filling factor in the cavity could be as large as 25%.

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