HOT GAS IN THE LISM: SOFT X-RAY OBSERVATIONS

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

THE SOFT X-RAY DIFFUSE BACKGROUND: IMPLICATIONS FOR THE NATURE OF THE LOCAL INTERSTELLAR MEDIUM

Dan McCammon
Physics Dept., Univ. of Wisconsin, Madison

ABSTRACT

Observations of the diffuse X-ray background in the B and C bands (130-188 eV and 160-284 eV, respectively) provide convincing evidence for the existence of high-temperature interstellar gas. Since the opacity of normal interstellar material is very high, we must assume that the soft X-ray flux observed in the galactic plane originates within a few hundred parsecs of the Sun. The intensity and B/C ratio of this low-latitude flux can be provided by emission from an equilibrium plasma with normal abundances, $T = 10^{6.0}$ K, and 0.0019 cm^{-6} pc emission measure. More sophisticated nonequilibrium models of material heated by a supernova blast wave would reduce the required emission measure somewhat, but not by so much as a factor of two. Arbitrarily limiting the pressure to 10^4 cm^{-3} K gives a maximum density of 0.005 cm^{-3} and a minimum radius for the emitting region of 75 pc. This fits in well with UV interstellar absorption measurements which indicate that the ISM is very deficient in neutral hydrogen out to $\sim$100 pc from the Sun.

The constancy of the observed B/C ratio implies that there are less than 5×10^{19} cm^{-2} variations in any cooler material lying between us and the bulk of the emission. This is consistent with the much smaller column densities of neutral or partially ionized material detected in the solar neighborhood through UV absorption measurements, but the organization of the cooler gas and its interaction with the coronal material require further investigation.

X-ray intensities at high latitudes are larger than those in the plane by as much as a factor of three. The fluctuations show a global anti-correlation with H I column density which suggests that they might be caused by variations in the transmission of X-rays from an extragalactic source, such as a galactic halo or corona. Such models are very difficult to reconcile quantitatively with existing H I measurements, however, and it seems more likely that the bulk of the high-latitude excess is produced by an extension of the unabsorbed interstellar emission in those directions with the remaining fluctuations produced by a combination of absorption and displacement by embedded cooler material, or possibly by transmission of flux from a hot halo.

While it would be most interesting to resolve this point because of its impact on the nature of the galactic halo and the high-latitude H I distribution, it does not greatly affect the amount of hot gas which apparently exists in the solar neighborhood: an isotropic emitting region with only the emission measure required by the average intensity near the galactic plane would account for about two-thirds of the integrated B and C band flux observed at the Earth. The total energy flux is $\sim1\times10^{-6}$ ergs cm^{-2} s^{-1} if we

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

assume a thermal equilibrium spectrum.

INTRODUCTION

A rather large body of data now exists which pertains to the nature and distribution of interstellar material within $\sim$100 pc of the Sun. Models are available which satisfactarily explain various subsets of these data, but it is not obvious that they can all be combined in any physically reasonable way.

Rather than giving a model to explain the X-ray data which would contain oversimplifications and misinterpretations making it impossible to reconcile with other kinds of observations, I will try to present the constraints introduced by the X-ray observations which must be satisfied by any general model of the local ISM. Two simplified models illustrating how some of these might be met are given near the end.

OBSERVATIONS

Maps of the diffuse X-ray emission in galactic coordinates are show in Figures 1 and 2 for the B and C bands, respectively. The B band responds from approximately 130 eV up to the boron K-shell absorption edge at 188 eV. The C band extends from about 160 eV to the carbon cutoff at 284 eV. More detailed data can be found in McCammon et al. (1983), but the most important features can be summarized as follows:

1. The B and C band maps appear very similar, with the exception of a northern-hemisphere feature near $\ell=30^0$ that has been identified with the North Polar Spur.
2. There is a finite flux in the galactic plane which is approximately the same at all longitudes.
3. The observed flux is generally higher by a factor of two to three at high latitudes. A large-scale anticorrelation with H I column density exists which becomes quite detailed in certain parts of the sky.

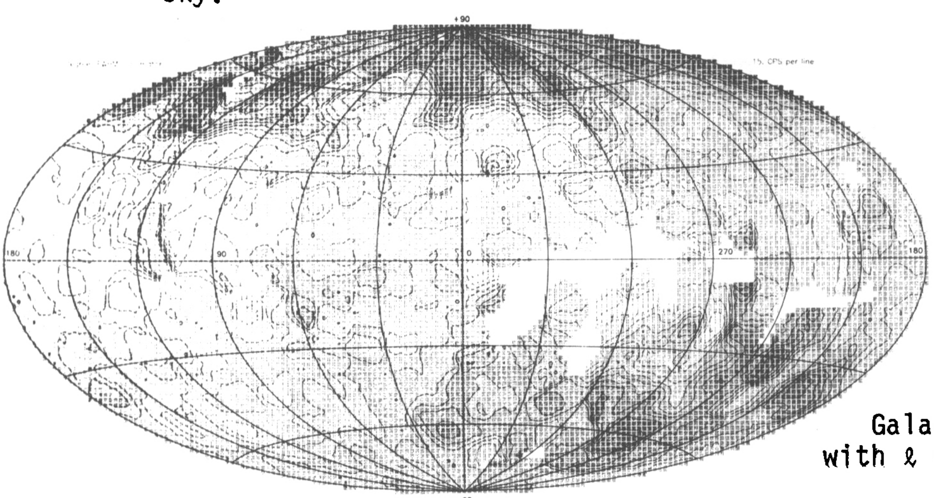

Fig. 1-- B band (130-188 eV) map.

Galactic coordinates with ℓ = 0^0 at center.

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

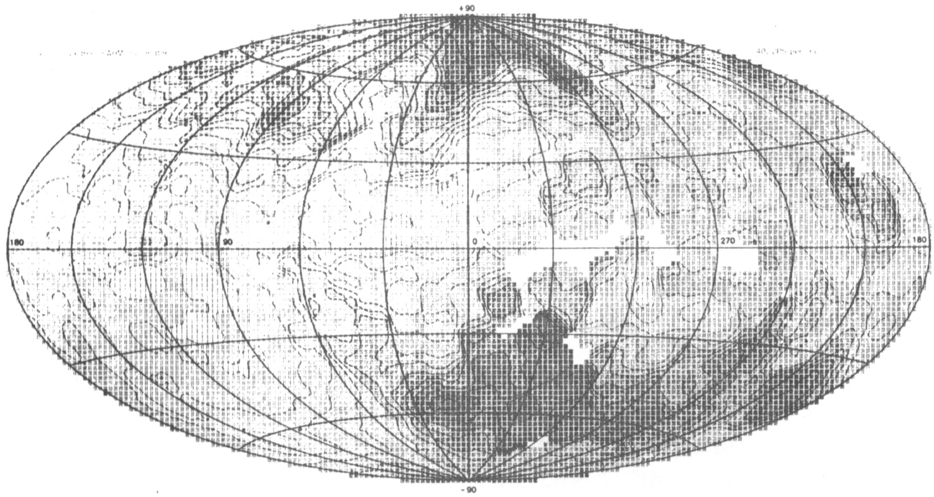

Fig. 2 --C band (160-284 eV) map.

DISCUSSION

The interaction of these X-rays with interstellar material is almost entirely due to photoelectric absorption. The mean free path for B band is about 5.6×10^{19} atoms cm^{-2} and that for C band is about 1.3×10^{20} cm^{-2}. About one third of the absorption is due to hydrogen and almost all of the remainder is due to helium.

The arguments that the X-rays are produced primarily as thermal radiation from a hot component of the interstellar gas near the Sun can be summarized as follows:

1. The rather short mean free paths imply that the X-ray flux observed near the plane, at least, must originate within a few hundred parsecs of the Sun.

2. The small-scale smoothness would require a space density of discrete sources equal at least to that of all stars. Stars provide less than 3% of the flux observed in these bands (Rosner et al., 1981). Therefore the source must be truly diffuse.

3. No non-thermal diffuse emission mechanism has been proposed which is not in serious conflict with other observations. We therefore assume that the source is thermal emission from hot interstellar gas.

4. For emission from a plasma in thermal equilibrium (Raymond and Smith, 1979) the observed B/C ratio implies a temperature near 1×10^6 K. The average intensity in the galactic plane requires an emission measure near 0.002 cm^{-6} pc. With a filling factor of

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

unity over a 75 pc pathlength, this gives a density ~ 0.005 cm^{-3} and a pressure of $\sim 10^4$ cm^{-3} K. Including non-equilibrium effects reduces the required emission measure, but by less than a factor of two. It also will provide the observed B/C ratio over a wider range of temperature (Cox and Anderson, 1982; Edgar and Cox, 1983).

5. At these temperatures, the emission is almost entirely in lines of the partially ionized heavy elements, even for heavily depleted material. There is strong observational evidence for emission lines from the region within Loop I, and weaker evidence for other parts of the diffuse background (Inoue et al., 1979; Schnopper et al., 1982; Rocchia et al., 1984).

With any diffuse background, it can be difficult to demonstrate that it is indeed coming from where you think it is, rather than, say, the solar wind, the upper atmosphere, or just background in the intrument. We can offer the following arguments:

1. A few features are identifiable with known objects, such as the North Polar Spur. However, these are probably not part of the general emission, and they have somewhat different specta.

2. The lack of parallax in other features requires them to be at a distance greater than 40 pc.

3. The above argument does not apply to the minimum observed flux level. This level accounts for 60% of the total B and C band X-ray flux at the earth if it is assumed to be isotropic, and its removal would greatly alter the apparent connection between the soft X-rays and the local ISN, We have primarily the following evidence for its origin beyond the solar system:

    a. The Wisconsin observations were made from sounding rockets over almost a full solar cycle, with little evidence for variability on scales of minutes, weeks or years.

    b. A map at energies comparable to our C band has been made using data from a quite different instrument on the SAS-C satellite (Marshall and Clark, 1984). It is in excellent agreement with the Wisconsin C band map.

    c. The broad-band spectrum of this component is the same as that of the features (which are known to be at $D > 40$ pc). This would have to be coincidence if the isotropic component were more local.

The true location of the X-ray emitting material could most readily be determined by looking for absorption by objects with known distances. The few such objects tried so far are at distances $\gtrsim 150$ pc, and none has showed any absorption. Column densities observed in UV absorption within 75 pc of the Sun are for the most part less than 1 x 10^{19} cm^{-2}, and would be difficult to observe, even in the B band. If X-rays at still lower energies can be shown to be coming from the same material as the B and C band X-rays, they would make a more sensitive probe for these small column densities, and should enable us to pin down the location of the emitting material much more precisely. Meanwhile, if molecular clouds or other such objects with N_H $\sim 5 \times 10^{19}$ or greater can be identified and located within the solar neighborhood, they could be looked for on the existing C and B band maps.

CONSTRAINTS

A more detailed examination of the B and C band maps leads to the following conclusions:

1. The close tracking of the intensities in these two energy bands implies that the majority of the B band emission is either from the same material emitting the C band X-rays or from material closely associated with it in space.

2. There is a general anticorrelation of X-ray intensity and H I column density as measured by its 21 cm emission. In some parts of the sky a rather good fit is obtained to a partially absorbed model of the form $I = I_0 + I_1 \exp(\sigma_{eff} \times N_{HI})$ while in other parts of the sky there is a very large scatter (Marshall and Clark, 1984).

3. The apparent cross section, σ_{eff}, required to fit the above model is smaller than the expected cross section of interstellar material by a factor of $\sim$0.65 in C band and $\sim$0.35 for the B band. This makes the apparent cross sections almost the same for the two bands, where a factor of two difference is expected because of the E^{-3} dependence of photoelectric cross sections.

4. An exception to (3) is found for the B and C band X-ray emission supposed to be associated with the North Polar Spur. The spatial variation of this is consistent with its being absorbed with normal interstellar cross sections by the large concentration of gas extending north from the galactic plane at these longitudes which has been located a distance of 75 - 120 pc. We therefore assume that we are looking at a bright portion of the limb of Loop I which lies somewhat beyond this gas.

Point (2) above causes the greatest difficulties in interpreting the soft X-ray background. A simple way of handling it is to assume that essentially all of the interstellar gas at intermediate and high latitudes is clumped into randomly distributed clouds with average thickness $\sim 2 \times 10^{20}$ cm^{-2}. Such clouds would be optically thick to both B and C band X-rays, but still thin to 21 cm radiation. This would reduce the apparent cross sections in both bands to approximately the derived values. One can then identify I_0 with an isotropic local component produced by 10^6 K gas in a spherical cavity surrounding the Sun and providing the X-ray flux

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

observed in the plane, and I_1 with an extensive galactic corona or other source at approximately the same temperature which lies beyond the galactic H I distribution.

This model is simple and attractive, and it is not very difficult to explain the parts of the sky where the correlation is poor as being due to random variations in I_0 or I_1. The major problem is that 21 cm observations measure rather directly those properties of the H I distribution which are important to its apparent X-ray absorption, and existing data seem inconsistent with the existence of the required clumping on any angular scale (Jahoda et al., 1984, and references therein). This two-component model seems viable only if some other way of reducing the apparent cross sections can be found.

Another scenario has the local cavity spatially extended at high latitudes where the ambient gas density is lower. In directions where the extent of the hot gas is greatest, there is the least room left for neutral gas beyond it, and this displacement effect could be the source of most of the anticorrelation.

In this case, it is somewhat troubling that the detailed anticorrelation is as good as it is observed to be in some areas. However, these areas tend to be ones where the total H I column density is very low, and it is possible that a hot corona or other extragalactic source exists, and that transmission of some of this flux by the galactic gas with normal cross sections provides the more detailed anticorrelation, but only a small fraction of the observed X-ray flux.

A theoretical difficulty with the displacement explanation for anticorrelation is that models of supernova blast waves in existing cavities show most of the X-ray emission coming from a thin shell at the boundary of the cavity (Cox and Anderson, 1982; Edgar and Cox, 1983). This tends to make the intensity observed from inside the cavity simply a surface-brightness effect, independent of the extent. It should be possible to produce an anticorrelation of X-ray intensity with the density of the material the blast wave finds at the cavity boundary if the age is properly chosen, but it would be surprising to find the space density so closely related to total column density as the X-rays appear to be in some directions.

We note that both of the above models require the majority of the observed X-rays to be produced in a region surrounding the Sun which contains little cooler material. Either of the models also at least allows the existence of a hot galactic corona of approximately the same intrinsic luminosity.

THE DIFFUSE BACKGROUND AT HIGHER ENERGIES

The M band (440-1100 eV) may or may not be at all related to the local interstellar medium. As can be seen in Fig. 3, the spatial distribution

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

is entirely different from that of the B and C bands. This is not surprising, since the mean free path in the interstellar medium is now a kiloparsec or so. What is surprising is that aside from the large feature in the direction of the galactic center, the flux is very nearly isotropic. In particular, it shows little tendency to either go up in the plane, as would be expected for a source associated with the galactic disk, or down in the plane, as would be expected from absorption of a source lying outside the disk.

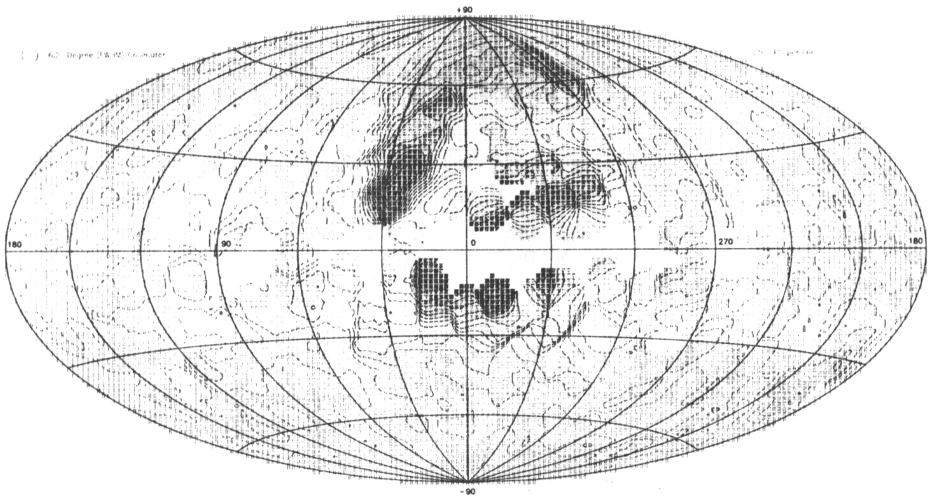

Fig. 3-- M band (440-1100 eV) map.
Galactic coordinates with $\ell=0^0$ at center.

The bright area on the M band map corresponds fairly well with the interior of Loop I, and most of this emission may be associated with it. Possible sources of the remainder include an extrapolation of the extragalactic power-law spectrum observed above 2 keV, which provide about half the high latitude M band X-rays, and dM stars, which could provide up to 25% of the flux seen near the plane (Rosner et al., 1981), and help fill in the absorption dip in the extragalactic contribution. Additional flux at high latitudes could be provided by either a hot component of the halo, or by emission from the local hot cavity. A distribution of structures similar to Loop I could provide additional flux in the plane.

A very reasonable model can be constructed which balances contributions from these four anisotropic sources to produce an isotropic total (Sanders et al., 1982), and this may turn out to be correct. One would be more comfortable of course, with obtaining an isotropic flux from an inherently isotropic source, which would have to be local to the solar neighborhood. The interior of the local cavity is a candidate, but current blast wave models do not easily make very many M band X-rays. It would also probably require that the extragalactic power law spectrum turn over somewhere between 1 and 2 keV.

https://doi.org/10.1017/S0252921100098183 Published online by Cambridge University Press

SUMMARY

We can briefly summarize the constraints introduced by diffuse X-ray observations for models of the local ISM and make suggestions for further observations:

1. Gas with a temperature near $10^{6.0}$K and an emission measure near 2×10^{-3} cm^{-6} pc must exist in all directions near the Sun. The tracking of the B and C band intensities seems to rule out any concentrations of cool material between us and the bulk of this emission with spatial extents greater than $\sim 6^0$ and column densities greater than $\sim 4 \times 10^{19}$ cm^{-2}.

2. The H I concentration extending northward from the galactic plane near $\ell = 20^0$ with a distance believed to be 75 - 120 pc must lie beyond most of the local emitting region, but appears to lie between us and the North Polar Spur which is assumed to be the limb of Loop 1.

3. A mechanism must be provided to supply the observed anticorrelation of the soft X-ray intensity and H I column density which can explain its apparent lack of energy dependence.

4. It would be most useful to locate and observe optically thick targets within $\sim$100 pc of the Sun to determine the extent of the local X-ray emission in various directions.

5. Similar shadowing experiments should help resolve the very interesting question of the origin of the M band X-rays. Much larger column densities are required for the absorbers, but they could be fairly small; ROSAT should be capable of making such measurements reliably on features from 1 arcmin up to about a degree.

The Wisconsin diffuse X-ray observations have depended on the work of a large number of people over an extended time period, and while I can acknowledge all of them anonymously,I should name in particular D. N. Burrows, W. L. Kraushaar, and W. T. Sanders. This work was supported in part by NASA grant GL 50-002-004.

REFERENCES

Cox, D. P., and Anderson, P. R. 1982, Ap. J., **253**, 268.
Edgar, R. J., and Cox, D. P. 1983, Ap. J., submitted.
Inoue, H., Koyama, K., Matsuoka, M., Ohashi, T., Tanaka, Y., and Tsunemi, H. 1979, Ap. J. (Letters), **227**, L85.
Jahoda, K., McCammon, D., Dickey, J. M., and Lockman, F. J. 1984, Ap. J., submitted.
Marshall, F. J., and Clark, G. W. 1984, Ap. J., in press.
McCammon, D., Burrows, D. N., Sanders, W. T., and Kraushaar, W. L. 1983,

Ap. J., 269, 107.
Raymond, J. C., and Smith, B. W. 1977, Ap. J. Suppl., 35, 419.
______. 1979, private communication (update to Raymond and Smith 1977).
Rocchia, R., Arnaud, M., Blondel, C., Cheron, C., Christy, J. C., Rothenflug, R., Schnopper, H. W., and Delvaille, J. P. 1984, Astr. Ap., 130, 53.
Rosner, R., Avni, Y., Bookbinder, J., Giaconni, R., Golub, L., Harnden, F. R. Jr., Maxson, C. W., Topka, K., and Vaiana, G. S. 1981, Ap. J. (Letters), 249, L5.
Sanders, W. T., Burrows, D. N., Kraushaar, W. L., and McCammon, D. 1982, in IAU Symposium 101, Supernova Remnants and their X-ray Emission, ed. J. Danziger and P. Gorenstein (Dordrecht: Reidel).
Schnopper, H. W., Delvaille, J. P., Rocchia, R., Blondel, C., Cheron, C., Christy, J. C., Ducros, R., Koch, L., and Rothenflug, R. 1982, Ap. J., 253, 131.