LARGE SCALE FEATURES OF THE HOT COMPONENT OF THE INTERSTELLAR MEDIUM

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The interstellar medium contains identifiable hot plasma clouds occupying up to about 35% of the volume of the local galactic disc. The temperature of these clouds is not uniform but ranges from 10^5 up to 4×10^6°K. Besides the high temperature which places the emission spectrum in the soft x-ray band, the implied pressure of the hot plasma compared to the cooler gas reveals the importance of this component in determining the motions and evolution of the cooler gas in the disc, as well as providing a source of hot gas which may extend above the galactic disc to form a corona. The following report presents data from the A-2 soft x-ray experiment on the HEAO-1 spacecraft concerning the large scale features of this gas. These features will be interpreted in terms of the late phases of supernovae expansion, multiple supernovae and the possible creation of a hot halo surrounding the region of the galactic nucleus.

INTRODUCTION

The low energy (0.1-1.4 keV) diffuse celestial X-ray emission is thought to be dominated by emission features originating mostly from hot plasma clouds in our galaxy. The very strong dependence of the photoelectric cross section upon energy implies that within this energy band we are sampling regions of the galaxy from a few tens of parsecs at the lowest energy up to several kiloparsecs at the upper end of the range in the galactic disk. At high galactic latitude, however, even at 0.2 keV it is possible to obtain information from sources outside of the galaxy with only moderate attenuation. The hot plasma clouds emitting the x-rays are most probably the remnants of old supernovae and interstellar gas heated by the expanding shock waves of these remnants. Results from the HEAO-1 A-2 Low Energy Detectors (LED's) on large scale features of the galactic diffuse x-ray emission are presented in the following sections.

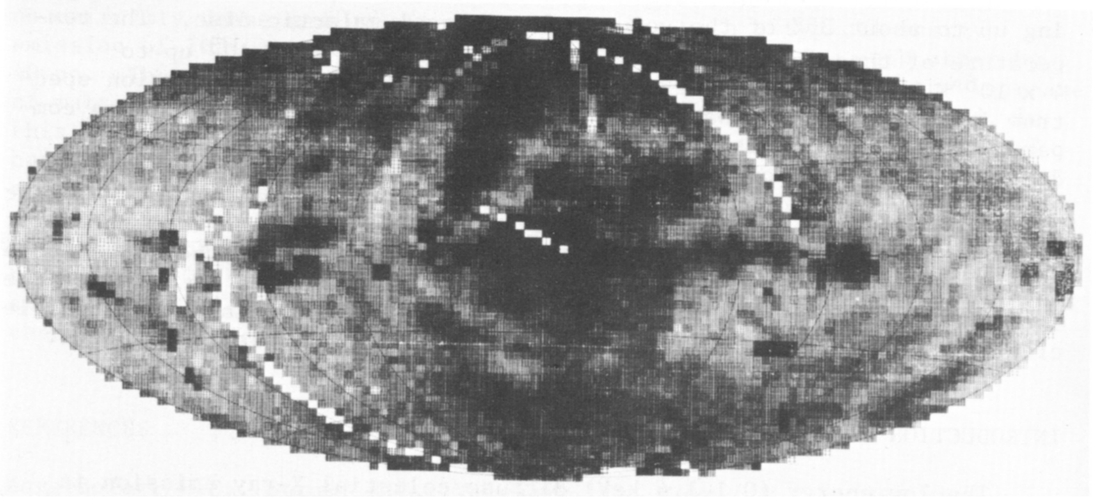
THE OBSERVATIONS

Maps of the diffuse soft x-ray emission have been constructed using

J. Danziger and P. Gorenstein (eds.), Supernova Remnants and their X-Ray Emission, 347–355.

https://doi.org/10.1017/S0074180900034100 Published online by Cambridge University Press

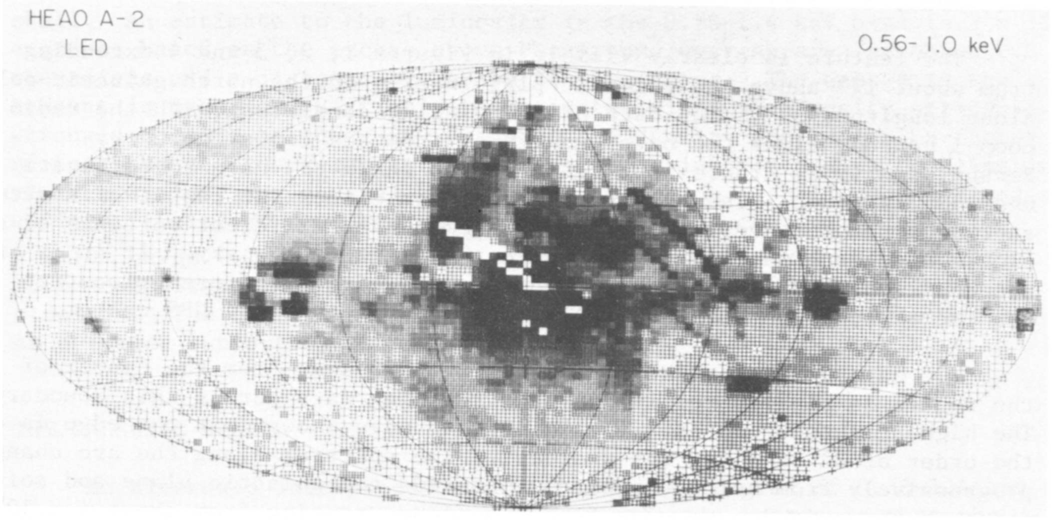
data from the 3° x 3° collimator of one LED on HEAO-1. The detectors have been described by Rothschild et al 1979. By utilizing the pulse height data which is telemetered every 10.24 seconds, maps in four energy bands have been created: 0.18-0.54 keV, 0.56-1.0, 1.0-1.4 keV and 1.4-2.7 keV. The data were all obtained from the second layer of the detector to avoid electron contamination which was found to be present at all points in the HEAO-1 orbit. The 10.24 second accumulation time adds an additional 2° to the angular resolution along the direction of the scan path. The data have been binned in approximately 3° x 3° cells on the sky. The resultant maps for the energy bands 0.18-2.7 keV, 0.18-0.56 keV, 0.56-1.0 and 1.0-1.4 keV are displayed in Figures 1 through 4. The 0.18-2.7 keV data are obtained from a rate scaler which was read out every 1.28 seconds, resulting in better angular resolution than the data obtained in the other energy bands. The highest energy data is omitted, since this map shows no large features at the level of the noise in the map. The white areas of the maps are regions not sampled during the survey.



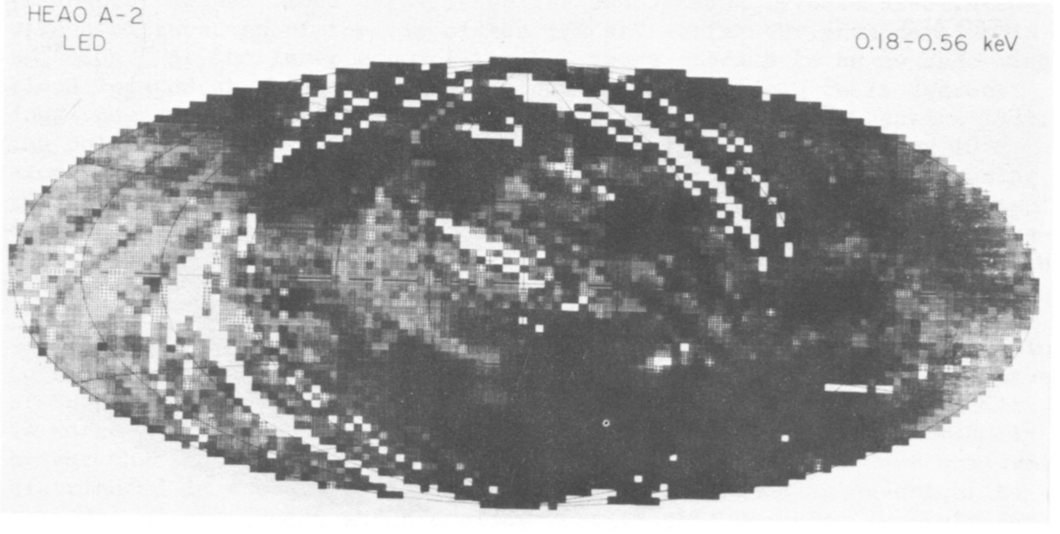
The 0.18-2.7 keV map of the diffuse x-ray background. The bin size is approximately 3° x 3° varying somewhat from the center of the map toward the Galactic Center to the edge of the Aitoff projection. White streaks and bins are regions of no data. The North Galactic Pole is at the top.

THE LARGE SCALE FEATURES

A number of extended regions of soft x-ray emission have been reported in the literature and are presented here with somewhat better angular resolution and sensitivity than displayed before, except in the cases of the Gemini-Monoceros Ring and the Cygnus Superbubble which have been published on the basis of HEAO-1 data. In general the large angular diameter regions are nearby (< 2 kpc), have temperatures between about two and four million degrees, and are probably associated with one or more supernova explosions which occurred at times greater than 10^4 years ago. The following discussion is organized in terms of the angular size of the feature,



The 0.18-0.56 keV map of the diffuse x-ray background. Very dark narrow linear features (streaks) are spurious and should be ignored.



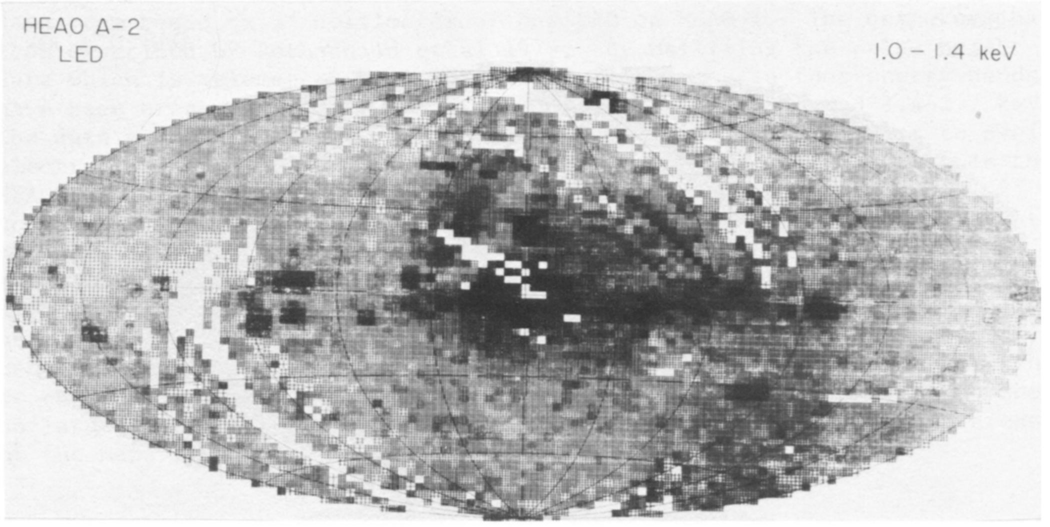
The 0.56-1.0 keV map of the diffuse x-ray background.

the largest diameter first.

NORTH POLAR SPUR

The association of the radio feature known as the North Polar Spur with an old supernova remnant was first suggested by Hanbury Brown et al., 1960. The X-ray emission has been studied by Bunner et al., 1972, Cruddace et al., 1976, Borken and Iwan 1977 and recently by Rocchia et

https://doi.org/10.1017/S0074180900034100 Published online by Cambridge University Press



The 1.0-1.4 keV map of the diffuse x-ray background.

al., 1983.

The feature is clearly visible in Figures 1, 2, 3 and 4 extending from about 12° above the galactic plane nearly to the north galactic pole along longitude 30°. The data are marginally consistent with the radio Loop I contour along the outer edge away from the center noted by Berkhuijsen 1972. There is a tendency for the x-ray data to bifrucate near 30° latitude. The bifrucation could be either the result of a second supernova remnant overlapping the NPS remnant or different portions of a single expanding shell projected onto the plane of the sky. If it is from a second supernova explosion the contour suggests a different location for the explosion, closer to the galactic plane than the NPS center.

The edge of the bright portion of the NPS away from the center of the region is clearly resolved by the scanning data across this boundary. The highest resolution data (1.5°) on this edge shows that the edge is of the order of 2° to 3° at its sharpest. The spectrum along the arc changes progressively from being the hardest towards the galactic plane and softening as the emission recedes from the plane, ranging from about 4×10^6°K near the plane and decreasing to about 2×10^6°K at the highest latitudes. There is a clear indication of absorption in the 1/4 keV channel at about 30° latitude, since presumably the plasma responsible for the radiation provides photons in this channel with an increasing surface brightness all the way down to the extreme tip of the spur at about 12° latitude where the 0.5-1.0 keV flux is greatest. An absorbing column of at least 6×10^{20} hydrogen atoms/cm^2 using the cross section of Cruddace et al. 1974 is required to account for the attenuation of the 1/4 keV x-rays. Such absorption is comparable to the total 21 centimeter column density in this direction. There does not appear to be a sharp gradient in the 21 cm data at the point of disappearance of the 1/4 keV flux although a triangular shaped cloud of HI in Heiles and Jenkins 1976 is associated with a bifrucation of the tip of the 1/4 keV surface brightness of the emission. At the inner edge of the NPS there appears to be an absorbing cloud located at about 35 to 40 degrees latitude and 10 to 15 degrees longitude associated with an HI wisp visible in Heiles and Jenkins 1976. The column density in X-rays through the cloud must be about 2×10^{20} atoms/cm^2, which implies a mean density of $4(\frac{d}{100}\text{ pc})$ atoms/cm^3 assuming the wisp is as deep as it is wide in linear dimension and d is the wisp's distance. A measure of the distance to the wisp would provide some constraints to the size of the local hot cavity in that direction, since the 1/4 keV flux is not less than the mean toward this feature.

In Figure 1, a large extended region of emission is present interior to the radio boundary of Loop I. By ascribing this radiation to the shell of Loop I, an upper bound to the total luminosity can be obtained. It is worth pointing out that the edge along longitude 30° is sufficiently bright that the entire shell should be visible if emission were uniformly distributed in the shell. Some of the interior region is as bright as the edge of the shell, which implies that if this emission is truly in the emitting volume the volume emissivity must be nearly an order of magnitude greater than in the observed edge, since the path length through the center of the shell is so much less than the path through the edge of the shell. An estimate to the luminosity in the 0.18-1.4 keV band is 2×10^{35} ergs/sec based on the excess above background over an area of about 0.2 steradians and a distance of 240 pc to the center. The energy in the remnant is much more difficult to estimate, since the density structure strongly couples to the x-ray emission. A density contrast of a factor of four changes the x-ray emission from the brightest region to being invisible against the general background. Based on a shell geometry and a uniform filling of the observed shell, the energy content is roughly 9×10^{51} ergs. This is high for a single supernova explosion and lead Borken and Iwan to suggest the region is the result of at least two explosions. The bifrucated shell mentioned earlier could be interpreted as evidence supporting this conjecture.

THE GALACTIC BULGE

An alternate interpretation of the intense region of 0.56-1.4 keV emission in the general direction of the galactic center is that the emission is in fact originating from a cloud of hot plasma surrounding the galactic center and extending out to some 2.5 kpc from the center. The absorption by neutral gas at these energies does not preclude this interpretation for the emission a few degrees on either side of the galactic plane. Near the plane, sources fill in any dip that might be expected from the neutral gas absorption.

If we take this emission to originate at a mean distance of 10 kpc, the luminosity is roughly 3×10^{38} ergs/s at a temperature of 3×10^{6}°K. If the region is uniformly filled, the mean density is 0.003 electrons/cm^3 and the total energy content is 10^{55} ergs. Assuming that the gas in this region is flowing outward roughly at the thermal velocity, the crossing time is about 10^7 years. Since the cooling time scale is of the order of 10^9 years, evaporation is the dominant loss mechanism. The gravitational escape velocity, assuming the material partakes of the local galactic rotation is of the same order as the thermal velocity, which means the evaporation time scale is probably greater than 10^7 years. In order to replace the 10^{55} ergs in a time greater than 10^7 years, about one SN of energy must feed the bulge region every 10^3 years, a plausible rate for the stellar content.

Clearly much more work is required to establish the distance to this feature surrounding the direction of the galactic center. It is possibly that the emission originates at intermediate distances between the galactic center and the NPS in bubbles such as the one observed in Cygnus (Cash et al 1979). However, in order for these bubbles to extend out of the plane by nearly 20°, they must either be larger in radius than the Cygnus superbubble or nearer. There is no known OB association in the direction of the galactic center nearly the size of the Cygnus OB association. Consider further that the Orion association does not exhibit such a bubble even though it is closer and contains more OB stars than the Cygnus association. Thus, the emission feature is quite possibly associated with the galactic center.

THE ERIDANUS REGION

A bright region in Eridanus ($\ell \sim 205$, $b \sim -50$) has been noted by Davidson et al., 1972, Williamson et al., 1974, and Long et al., 1977. This region is revealed clearly on the 1/4 keV map as an arc of a circle distorted by the Aitoff projection at the edge of the map. An HI feature has been observed by Heiles 1976, which follows the x-ray arc quite precisely. It is possible that this feature represents an old SNR expanding into the low density medium rather far off of the galactic plane. The brightest portion of the remnant which is away from the plane is possibly the result of an absorption effect in view of the HI distribution observed by Heiles which surrounds the x-ray shell and shows low velocity gas obscuring the portion nearer to the plane than about -30° as well as obscuration for the portion at longitudes less than about 200° except near the extreme edge of the loop near latitude -50°. As Heiles points out, this is one of the best examples of a correlated x-ray and HI shell. A detailed study of this feature is in preparation. The x-ray parameters lead to the following estimates for the physical conditions in the remnant for a distance of d_{150} of 150 pc: $n_e \simeq 0.03/\mathrm{cm}^3\ d_{150}^{-1/2}$, $E_o = 8 \times 10^{50}$ ergs, $T \sim 2 \times 10^6$°K, $M_{hotshell} \simeq 8M_\odot\ d_{150}^{5/2}$ and an adiabatic expansion age of about 4×10^4 years. Heiles estimates the mass of the HI shell at $7.3 \times 10^4\ d_{150}^2\ M_\odot$ which far exceeds the mass of hot gas. Such a gross difference has not been observed in other supernova remnants, and further discussion will be reserved for a future publication.

THE VELA REGION

Another region of extended emission which has not been noted by previous investigations is a low surface brightness region surrounding the Vela supernova remnant. The total emission is about 0.1 of the Vela SNR flux. Assuming that this emission originates from a uniform hot cloud at the distance of Vela which is taken to be 450 pc, the luminosity is 4×10^{34} ergs/sec if the temperature and column density of hydrogen are the same as the Vela remnant ($\sim 2.6 \times 10^{6}$°K and $2 \times 10^{20}/cm^2$, Moore and Garmire, 1976). The low surface brightness feature may be an earlier supernova in the same region. The outline fits roughly the angular extent of the Gum Nebula (Bok, 1971). Bok suggests that the Gum Nebula may be somewhat closer than the nebula associated with the Vela X and PSR0833-45 region.

THE LUPIS-CENTARUS REGION

There is an extended region of soft X-ray emission in the Lupis-Centarus constellations centered at about $\ell^6 = 320°$ and $b^4 = +20°$ extending over roughly 500 sq. deg. Several supernova remnants are bounded by this more extended feature, the Lupis Loop, the SN 1006 remnant and H1538-32 (Riegler et al 1980). The extended emission feature is comparable in size to the Gum Nebula in x-rays and of about the same surface brightness. Since the distance is undetermined at this time, estimates of the luminosity can not be made. It is possible that this feature extends all the way down to the galactic plane and that a lane of absorbing material prevents the observation of the true angular extent of the region based on the data shown in Figure 3. There is a clear displacement of the centroid of emission of this hot cloud with energy as can be noted between Figures 2 and 3, where the low energy data shows the bulk of the emission coming from about 315° longitude and the next higher energy channel shows the emission centered at about 340° longitude. In fact the data from the two energy bands barely overlap at 330°. A similar displacement of emission is present in the North Polar Spur only in latitude rather than longitude. It is not possible to rule out that these are two separate regions of emission at different distances that overlap in projection along 330° longitude

DISCUSSION

The Cygnus Superbubble (Cash et al 1980) and the Gemini-Monoceros Ring (Nousek et al 1981) have been discussed in details previously. Several new features detected by the HEAO-1 A-2 experiment have been presented here, together with all sky maps in several energy bands which are sensitive to emission from elderly supernova remnants. The fact that of order four old remnants (age $\lesssim 10^5$ years) are observed out to a distance of 500 pc (this excludes the Cygnus object which appears to be a different phenomenon and is more distant) is consistent with a galactic supernova remnant production rate of about one every fifty years.

If we assume that the five large features observed are within 400 pc, are roughly 70 pc in radius, and the disc is 300 pc thick, then the observed shells fill about 20% of the available volume of the galactic disc. If we are inside one such shell and we interpret several features in the 1/4 keV map as being additional shells that are less well defined with respect to the general background, the filling factor can possibly reach 35%. Only by going to even older remnants which have completely lost their identities can the filling factor reach 50% or higher. The gas pressure in these shells is of the order of 3×10^5 k dynes/cm^2 versus typical cool gas pressures of 300 k dynes/cm^2, where k is Boltzmann's constant. This difference serves to illustrate the potential for this gas to control the dynamics of cool gas clouds in the galactic disc.

I would like to thank J. Nugent and R. Truax for computational assistance in constructing the maps and J. Nousek for useful comments. This work was supported by NASA contract number NAS5-26809.

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DISCUSSION

SANDERS: To answer the question of how far away is the 0.56-1.0 keV enhancement towards the galactic center, couldn't you use the column density of neutral hydrogen that you fit to your data to see if it's consistent with the extinction measured to the galactic center by other means?

GARMIRE: The problem here is made very difficult by the variations in the local emission which makes the subtraction of this emission from the more distant features uncertain and somewhat arbitrary. For this reason, I'm hesitant to quote a figure for the amount of X-ray absorption toward the direction of the galactic bulge region.

DAVELAAR: 1) Is there evidence for Loop IV emission in the HEAO-A2 maps? 2) Do you see indication for any connection between Loop I and possibly Loop IV?

GARMIRE: 1) It is not very clear, if present. 2) The only emission in the Loop IV region essentially overlaps Loop I. I don't see an obvious way to disentangle the projection effects.

DANZIGER: Does the extended region around Vela correspond to the optical extent of the Gum Nebula?

GARMIRE: Approximately, yes.

MCKEE: Garmire's model for Loop I involves a high energy for one SNR, whereas Cox described a one SNR model for the Loop. Could you reconcile this apparent discrepancy?

GARMIRE: The total energy content of the NPS (Loop I) is quite uncertain. The bifurcation of the shock front near $\ell \sim 30°$ and $b \sim 30°$ could be interpreted as evidence for a second SNR.

BLEEKER: What is the observational basis for the statement in your abstract that the interstellar medium is occupied with a dominant hot gas component of at least 50% (50%-90%)?

GARMIRE: The fraction of the local galaxy filled by identifiable features is up to 35%. Older features which have lost their identifiable structure undoubtedly exist and could double the filled volume with hot plasma over that obtained from identifiable features.