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The hot part of the interstellar medium

In the preparation of this chapter there arose issues of semantics. Specifically, what does the "hot part" mean in reference to the interstellar medium (ISM), and just what part of the hot ISM should be considered? As the original task for this chapter referred to the X-ray and EUV (extreme ultraviolet), appropriate temperatures are in the several 10^5 K to several 10^6 K range. In a Universe where the fundamental temperature is currently about 3 K and in a Galaxy where most of the material in the ISM has temperatures less than 10^4 K, any component at 10^6 K must have been produced by fairly extreme and unusually spectacular methods. The most common of these methods in the general galactic disk are supernovae, occasionally aided and abetted by the stellar winds of massive stars. However, as supernova remnants (SNRs) are ably covered elsewhere in this text (see Chapter 41), the topic for this chapter required further refinement. What happens to a SNR when it slips past middle age into its dotage? All of the visual features that allow a SNR to stand out clearly from the background fade: the shock fronts (the interface region between the expanding SNR and the undisturbed ISM) with occasionally spectacular radio, optical, and X-ray emission, and the hot and relatively dense interior with bright X-ray emission. As the SNR fades it also increases in size to become a more significant, or at least a more extensive part of the ISM. In essence it becomes old and boring, and fades into the woodwork; a pale ghost of its former self.

Thus the study of the hot ISM, at least in the galactic disk, is essentially a study of what happens to SNRs that have lost their identity, though there are exceptions. Although the study of hot plasmas in the halo of the galaxy may have cosmological considerations, there are ties to the disk through the galactic gravitational potential and through "chimneys," breakouts of SNRs through the confining cooler ISM of the disk which expel hot plasma into the halo (in this chapter the "halo" of the Galaxy is defined as the region of space above the neutral material of the disk, and includes both ionized and neutral gas associated with the Galaxy and affected by its gravitational potential; this is a fairly loose definition which extends from a couple of hundred parsecs to tens of kiloparsecs, or even farther, above the plane). For the purposes of this chapter, a partially sociological definition of the hot part of the interstellar medium will be used: that part of the ISM which is (1) observed in the 0.05 to 1.0 keV band as the soft X-ray diffuse background (SXRB) and EUV background, (2) associated with the Milky Way disk or halo, and (3) not claimed by others for studies of supernova remnants or stellar wind-blown bubbles. To simplify the presentation and to acknowledge that at least the observed part originates in general from some of the same plasmas, the EUV will be included with $\frac{1}{4}$ keV X-rays, despite the historical separation by NASA of the astrophysics and astronomy programs at 0.1 keV. Furthermore, by and large this chapter will focus on the $\frac{1}{4}$ keV SXRB because it is the dominant galactic background and, at least locally, it is the best understood. Besides, SNRs that are still emitting strongly at energies greater than $\frac{1}{4}$ keV typically still stand out clearly against the general background and fail consideration (3) above.

Despite the observational difficulties in the study of has-been SNRs and their lack of spectacular features (e.g., the wealth of structure revealed by the initial Chandra observations of the more youthful Cas A and Crab Nebula SNRs), a few true believers have pursued the study of the SXRB over the last 30 years with some diligence. Like X-ray astronomy in general, it is a field that has truly required the "Century of Space Science," as photons with energies of 0.05 to 1.0 keV travel at most millimeters in Earth's atmosphere at sea level. The detectors must therefore be placed above the atmosphere at altitudes of $\gtrsim$200 km. The SXRB

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required the advent of astronomical research sounding rockets in the late 1950s and early 1960s to provide the facility for its observation. Over three decades of study, the observations of the SXRB have progressed from limited regions of the sky provided by single sounding-rocket flights, to all-sky mosaics provided by multiple flights, to all-sky surveys provided by satellite-borne observatories.

The initial discovery of the $\frac{1}{4}$ keV SXRB in the late 1960s (Bowyer *et al.* 1968, Henry *et al.* 1968, Bunner *et al.* 1969) was interpreted in the context of an extragalactic background. This interpretation was an obvious one suggested by the general negative correlation between the surface brightness of the SXRB and the column density of galactic neutral hydrogen (H I)*, as well as the expectation that there could possibly be extensive X-ray emission from intergalactic space as the low-energy extension of the extragalactic background above 2 keV first observed by Giacconi *et al.* (1962). The negative correlation observed at $\frac{1}{4}$ keV was assumed to be due to the absorption of an isotropic X-ray flux of distant (extragalactic or galactic halo) origin by the foreground material of the galactic disk. The fact that the required absorption cross-sections were smaller than the theoretical values could be explained by possible clumping of the cooler ISM. The nonzero flux observed in the galactic plane, where the Galaxy is completely opaque to extragalactic photons in this energy range, was attributed to additional background components, of either non-cosmic (e.g., a charged-particle background) or cosmic (e.g., unresolved galactic point sources) origin. Thus, the first big step toward our understanding of the SXRB went, as will be shown, in somewhat the wrong direction. However, also from the first step, the study of the SXRB was correctly linked to the ISM, in this case cooler components of the ISM that can absorb an X-ray flux of distant origin and modulate its apparent surface brightness.

By its nature, the $\frac{1}{4}$ keV SXRB is closely linked to the cooler ISM, whether or not it originates in the galactic disk or as an extragalactic background. The column density of H I (N_H, the amount of material along a line of sight) required for unit optical depth for the absorption of X-rays by the ISM is shown in Figure 1 as a function of energy. In the $\frac{1}{4}$ keV energy range this is $N_H \sim 10^{20}\,\mathrm{cm}^{-2}$. Even at its minimum high-galactic-latitude column density ($N_H \sim 5 \times 10^{19}\,\mathrm{cm}^{-2}$), the Milky Way provides roughly half an optical depth of absorption as viewed from Earth for X-rays of extragalactic origin. At lower latitudes with longer path lengths

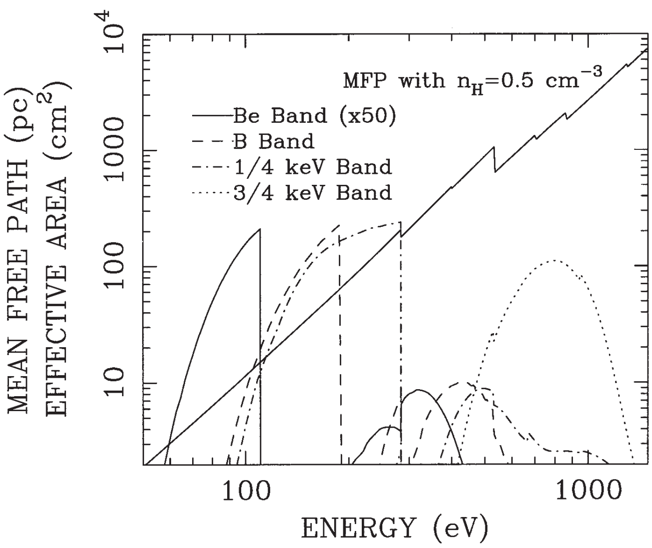

Figure 1 Average mean free path of EUV and soft X-ray photons in the Milky Way as a function of energy, along with typical band-response functions (detector effective areas) for a sample of soft X-ray and EUV detectors. The mean-free-path curve assumes a constant space density of $n_H = 0.5\,\mathrm{cm}^{-3}$ and uses Morrison and McCammon (1983) absorption cross-sections. The Be band response function is from the Wisconsin detector (Bloch *et al.* 1986), and has been multiplied by a factor of 50 for display purposes. The B band response curve is from the Wisconsin survey (McCammon *et al.* 1983). The band response functions of the $\frac{1}{4}$ keV and $\frac{3}{4}$ keV bands are from Rosat (Snowden *et al.* 1995). The band response functions show the sensitivities of the respective instruments as a function of energy (the larger the values, the more able they are to detect X-rays of that energy).

through the Galactic disk, one optical depth is reached after a path length of $\sim$100 pc, assuming a smoothly distributed ISM with a space density of 0.5 H I cm^{-3}.

EVOLUTION OF THE DATA

This section will focus on the data collected over the last three decades and how they influenced our understanding of the SXRB. It will not cover all contributions to the field (with apologies to those left out) but will hopefully give a feel for the evolution of the data. While some reference will be made to models for the origin of the SXRB, the detailed discussion of such models will be deferred to later in this chapter.

Initial observations and the early years

As noted above, observations of the SXRB have evolved from the results of a limited number of sounding-rocket

*Astronomy has the quaint convention of using roman numerals to indicate the ionization state of elements. However, a single "I" indicates neutral material. (In fact, the "I" is the label for the "first spectrum" of a given element, which by convention is the spectrum of the neutral overestimate.) Thus, H I refers to neutral hydrogen and H II refers to ionized hydrogen (otherwise known as a proton). The ion O VI referred to later in this chapter is five-times-ionized oxygen, or O^{5+}.

flights covering limited regions of the sky to all-sky surveys produced by orbiting observatories. The first published observation was the result of a sounding-rocket scan by Bowyer *et al*. (1968) which observed the northern Galactic hemisphere between the center and anticenter directions (the anticenter refers to the direction in the Galactic disk which from Earth is 180° from the galactic center), scanning over the galactic pole. They observed a distinct negative correlation between the surface brightness of the SXRB in the $\frac{1}{4}$ keV band and the column density of galactic neutral hydrogen that they attributed to the absorption of an extragalactic background. The fitted absorption cross-section was significantly less than the model prediction from atomic physics, a result which was left as having mostly unspecified strong implications for the ISM after a discussion of a possible incorrect value for the He/H ratio.* Higher X-ray intensities were observed in the direction of the galactic center, which were attributed to an anomalous emission component and interpreted as possible evidence for a galactic corona (a hot galactic halo). The Bowyer *et al*. results should be considered in the context of the results of Gursky *et al*. (1963) who had identified the possibility of an extragalactic background contribution in their data at energies above 2 keV, and the suggestion by Gould and Sciama (1964) and others that the intergalactic medium might emit strongly at softer (lower) X-ray energies.

Henry *et al*. (1968) reported the SXRB observation of another sounding-rocket flight, and like Bowyer *et al*. (1968) they observed extensive emission at $\frac{1}{4}$ keV. In their analysis, they ruled out galactic corona emission (the density of the corona would need to be unreasonably high) as well as emission from external galaxies and galactic point sources as the origin (because of both spectral considerations and the excessive magnitude of the required total flux), leaving the conclusion that the background arose as free–free emission (radiation from interactions between free electrons and positive ions) from a hot, dense intergalactic medium. Bowyer and Field (1969), when not explaining the differences between the Bowyer *et al*. (1968) and Henry *et al*. (1968) results, suggested that the counts observed in the galactic plane were due to an isotropic particle background, and that the apparent absorption cross-sections were reduced from the theoretical values by clumping of the absorbing medium.** The concept of a clumpy, X-ray-absorbing ISM would play a role of some controversy in models of the SXRB for the following 20 years.

*While the absorption column density is measured by the column density of neutral hydrogen, N_H, derived from 21 cm measurements of the ISM (21 cm is the wavelength of the neutral hydrogen electron spin-flip transition), the helium associated with the hydrogen provides roughly half of the physical absorption at $\frac{1}{4}$ keV. Therefore if the true He/H ratio is lower than assumed, the model absorption will be overestimated.

Bunner *et al*. (1969) presented the last of the initial triad of SXRB observations, and reported results which were more-or-less consistent with the previous two. In their analysis they considered three separate alternatives for aspects contributing to the angular structure of the $\frac{1}{4}$ keV SXRB:

1. The small effective absorption cross-sections were due, as in Bowyer and Field (1969), to clumping of the absorbing medium into optically thick clouds. Although they did not find the evidence for the existence of such clouds compelling, clumping of the H I into clouds of $N_H \sim 10^{21}$ cm^{-2} satisfied the intensity-dependence constraint of the $\frac{1}{4}$ keV data with absorption column density but was still consistent with the 0.5–1.0 keV data. However, even with the assumed clumping, an additional soft component was required to explain an excess of emission observed above the extrapolation of the extragalactic power law identified at higher energies.
2. The observed flux in the galactic plane was due to an unknown solar or terrestrial background. This assumption reduced the requirement for clumping of the ISM, but an additional, softer extragalactic emission component was still required.
3. The observed flux in the galactic plane was due to the superposition of unresolved galactic Population II sources (the older, more numerous, and less massive stars in the Galaxy, M dwarfs for example). The required source density, $\sim 10^{-2}$ pc^{-3}, was less than the population of known objects, and so could not be ruled out.

While there was some disagreement about the details of the observational results presented by the three groups, they were all consistent with requiring an emission component in excess of the extrapolation of the extragalactic power law observed above 2 keV to explain the background at $\frac{1}{4}$ keV. The "real" diffuse background was assumed to be extragalactic or galactic halo in origin while any residual flux from the galactic plane was assumed to be either noncosmic contamination or from unresolved point sources. Diffuse X-ray emission from the interstellar medium of the galactic disk was not yet considered.

**When the ISM is clumped into at least partially optically thick clouds which are not resolved by either the H I or SXRB observations, the effect is to reduce the apparent ability of the material to absorb a diffuse X-ray flux. For example, if the ISM is diffusely distributed then the absorption optical depth should just be the theoretical cross-section multiplied by the observed column density. However, if the ISM is clumped into unresolved "bricks," an X-ray would certainly be stopped by the brick, but the bricks would cover very little of the sky so most X-rays would be unaffected. Once the brick is optically thick it does not absorb more X-rays if you add more material to it, but more material is removed from the ISM, allowing more X-rays to pass between the bricks. The effective absorption cross-section is then reduced. Besides the effect of reduced cross-sections, the absorption becomes energy independent once the bricks are optically thick.

The 1970s

The 1970s were marked by the targeting of observations to attempt to determine the origin of the background and the expanded coverage of the soft X-ray sky. A significant role was played by the decade-long sounding-rocket campaign by the University of Wisconsin–Madison, Space Physics Laboratory under the direction of W.L. Kraushaar. One goal of the campaign was to determine the fraction, if any, of the observed background that was extragalactic in origin; a second goal was to survey the entire sky in the 0.1–10.0 keV band (see below). To address the first issue, the Small Magellanic Cloud (SMC) was scanned to search for the signature of shadowing. The use of "shadowing" here refers to the simple idea that a foreground object such as an H I cloud will absorb part or all of the X-ray emission originating behind it, thus casting a shadow in the light of the background source. This is analogous to the sky on a stormy day when it appears darker in directions where the clouds are thicker, or more starkly, when the Moon passes in front of the Sun during an eclipse. The result of the SMC study was that at least 75% of the observed $\frac{1}{4}$ keV SXRB originated in front of the SMC (McCammon *et al.* 1971). Another group, Long *et al.* (1975), searching for detailed negative correlation between the column density of galactic H I and the surface brightness of the SXRB, presented results for a sounding-rocket observation in the direction of the Large Magellanic Cloud. They found that greater than 90% of the observed $\frac{1}{4}$ keV background originated in front of the galactic H I in that direction; a direction which is relatively opaque to $\frac{1}{4}$ keV X-rays of distant origin if the ISM is not clumped.

With increasing sky coverage it became clearer that while there was certainly a general negative correlation between the SXRB surface brightness and the column density of H I (i.e., the plane-to-pole inverse variation of $N_{\rm H}$ and X-ray intensity), the evidence for detailed negative correlation was in general lacking (i.e., shadows cast by distinct clouds in the ISM). However, it should be remembered that the early detectors were mechanically collimated and typically had fields of view on the order of 10–50 square degrees (the Moon has an apparent diameter of about half a degree). In addition, the observation of the sky during a sounding-rocket flight was limited to around five minutes of useful data collection, so the observations were also photon limited.

An advantage of the Wisconsin data was a second, softer band provided by a detector with a boron filter (the B band, the boron $K\alpha$ absorption edge yields a high-energy cut-off of 0.188 keV, compared to the usual carbon $K\alpha$ absorption-edge cut-off of 0.284 keV for the C or $\frac{1}{4}$ keV band, see Figure 1). The theoretical effective ISM absorption cross-sections for the two bands differ by about a factor of 2; however, the hardness ratio (or X-ray color) of the observed intensities in the two bands remained relatively constant (with some structure) over a factor-of-3 variation in intensity and associated variation in column density (Fried *et al.* 1980). Two solutions for this discrepancy were that either the absorbing column of galactic H I was significantly clumped, eliminating any differential (in energy) absorption, or that the emission originated in front of the H I (e.g., Sanders *et al.* 1977). Hayakawa *et al.* (1978) came to the latter conclusion as well, that a majority of the diffuse Galactic X-ray background originated in a local region surrounding the Sun. They used spectral fitting of sounding-rocket data with the result that little or no interstellar absorption is required.

Another vital aspect of the SXRB became clear in the 1970s: the observed emission most likely had a thermal origin (emission from a hot plasma dominated by collisionally excited emission lines). For example, Williamson *et al.* (1974) discussed several non-thermal emission mechanisms and found them lacking. Synchrotron production (radiation produced by charged particles spiraling around magnetic field lines) failed because the required X-ray spectral index is much larger than that at radio wavelengths, and the lifetime of the required electrons ($>10^{13}$ eV in a 3 μG magnetic field reasonable for the Galaxy) is less than 10^4 years. The number of $\sim$250 MeV electrons required to produce the $\frac{1}{4}$ keV SXRB by Compton scattering (collisions between high-energy electrons and photons that increases the energy of the photon) off the 3 K background (the fossil radiation left over from the Big Bang) is unreasonably large as well. Thermal bremsstrahlung (free–free) emission from a hot plasma could produce the required spectral contribution but also required too high a space density for the plasmas, and thus excessive pressures, if galactic in origin (e.g., Henry *et al.* 1968). The inclusion of collisionally excited line emission from a thermal plasma (e.g., Cox and Tucker 1969) provided a much more efficient emission mechanism in the 0.1–1.0 keV energy range, reducing the required density for that plasma to a reasonable level for a galactic origin. Thus thermal emission from extended regions of hot plasma became the most likely candidate for the source of the SXRB. A galactic thermal origin became even more likely with the Copernicus observations of a nearly ubiquitous interstellar O VI absorption line (e.g., Jenkins 1978). The width of the ISM absorption lines in the spectra of Milky Way stars indicated that the O VI could only be produced by collisional excitation by a thermal plasma at $T \gtrsim 10^{5.5}$ K. While a plasma at this temperature is a bit too cool to be responsible for the observed $\frac{1}{4}$ keV emission, it is consistent with what could be expected from H I-cloud interfaces with a hotter plasma. De Korte *et al.* (1976) presented an analysis of the data from two sounding-rocket flights from the early 1970s. Using data from two detectors with markedly different window thicknesses (which creates a similar but not as strong an effect as having a separate

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