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HOT GAS IN THE GALAXY: WHAT DO WE KNOW FOR SURE?

W. T. Sanders

Department of Physics, University of Wisconsin-Madison, USA

RESUMEN

En la década pasada se lograron grandes avances en nuestra concepción del gas interestelar caliente de la Vía Láctea. El Diffuse X-ray Spectrometer obtuvo espectros del plano galáctico (esto es, de la Burbuja Local), en el rango 0.15–0.28 keV, que muestran líneas y mezclas de líneas de emisión. Los espectros confirman que el fondo de rayos-X suaves, en estas energías, es de origen térmico a aproximadamente 10^6 K, pero el espectro no puede ser bien ajustado con los modelos de emisión de plasma existentes. Los datos del satélite *ROSAT*, tanto de muestreo de todo el cielo como de observaciones puntuales, restringen las distancias del gas que emite dentro de la Burbuja Local, el medio interestelar local y el halo. Los datos confirman que la Burbuja Local tiene un tamaño de $\sim$ 100 pc y que el halo galáctico tiene dos componentes de gas caliente; una componente muy inhomogénea de 10^6 K y otra componente más caliente, de varios 10^6 K, cuya distribución es suave y sigue a la estructura general de la Galaxia. El satélite *ASCA* ha detectado emisión de plasmas a más de 10^7 K en la cresta galáctica, en dos regiones del centro galáctico y en el bulbo. Más recientemente, el micro calorímetro del experimento Wisconsin/Goddard con cohetes observó el espectro de la emisión difusa en $(l, b) \sim (90°, 60°)$, con un campo visual de 1 sr en el rango espectral 0.1–1 keV y con una resolución de $\sim$ 8 eV. Las líneas de O VII y O VIII son detectadas, pero sólo se obtienen límites superiores para las líneas esperadas de Fe XVII.

ABSTRACT

Major advances have been made in the past decade in our knowledge of the hot interstellar gas of our Milky Way galaxy. The Diffuse X-ray Spectrometer obtained spectra in the 0.15–0.28 keV range from the Galactic plane (i.e., from the Local Bubble) that show emission lines and blends. These spectra confirm that the soft X-ray background in this energy range is thermal in origin, at temperature roughly 10^6 K, but the spectra are not well fit by standard plasma emission models. Data from the *ROSAT* satellite, both from the all-sky survey and from pointed observations, have provided constraints on the distances to some of the hot gas emitting regions in the Local Bubble, the local ISM, and the Galactic halo. These data confirm that the local bubble is $\sim$ 100 pc in size, and they indicate the existence of two independent hot gas components in the Galactic halo: a patchy, localized lower temperature halo component near 10^6 K, and a smoother higher temperature halo component at several 10^6 K, with a spatial structure reflective of the overall structure of the galaxy. The *ASCA* satellite has observed emission from hot plasmas at temperatures above 10^7 K from the Galactic ridge, from two different galactic center components, and from the Galactic bulge. More recently, the Wisconsin/Goddard micro-calorimeter sounding rocket payload has observed the spectrum of the diffuse emission from $(l, b) \sim (90°, 60°)$ with a 1 sr field of view over the 0.1–1 keV spectral range with $\sim$ 8 eV resolution. Lines from O VII and O VIII are clearly seen, but there are only upper limits to the expected Fe XVII lines.

Key Words: **GALAXY: GENERAL — GALAXY: STRUCTURE — ISM: BUBBLES — ISM: GENERAL — X-RAYS: ISM**

What I would like to do in this talk is to summarize the observations of diffuse interstellar hot gas—meaning temperatures of order 10^6 K—in our Galaxy. Trying to cover such a broad range of observations means that I probably won't do a very good job describing any of them, so I apologize in advance and proceed.

1. SPATIAL STRUCTURE

The most comprehensive data set we have is that obtained by the *ROSAT* satellite—both its all-sky survey and its pointed observations. The *ROSAT* all-sky survey is presented as maps in 3 bands, 1/4 keV, 3/4 keV, and 1.5 keV, in Snowden et al. (1995b, 1997). In the 1/4 keV band map, we see X-rays characteristically emitted by plasmas with $T \sim 10^6$ K, but interstellar absorption is large, so we can see only out to an $N_{\rm H}$ of a few 10^{20} cm^{-2}, roughly 100–200 pc. In the 3/4 keV band, we are more sensitive to plasmas at $T \sim 3 \times 10^6$ K, and interstellar absorption is smaller, so we can see out to $N_{\rm H} \sim$ few 10^{21} cm^{-2}, several kpc. In the 1.5 keV band we are seeing plasmas with $T > 10^7$ K and we see through almost the entire Galaxy. The different structures that we see in these maps reflect the structure of the Galaxy on those different distance scales.

1.1. *The 1/4 keV Band*

Some of the bright features visible on the 1/4 keV band map have names or are associated with features seen at other wavelengths. A large arc extending from $(l, b) \sim (30°, 45°)$ through $(l, b) \sim (330°, 75°)$ and reaching as far as $(l, b) \sim (290°, 60°)$ is associated with the radio continuum North Polar Spur, which is part of radio Loop I (Berkhuijsen, Haslam, & Salter 1971). This Loop appears coincident with the edge of a superbubble associated with the Scorpius-Centaurus OB associations at a distance of $\sim$ 150 pc. This is the superbubble nearest to the Local Bubble. Another superbubble, several hundred pc away, is seen in Eridanus, roughly centered at $(l, b) \sim (205°, -40°)$. It is associated with the cavity generated and heated by the Orion OB stars (Reynolds & Ogden 1979; Snowden et al. 1995a; Guo et al. 1995). The Monogem Ring (Plucinsky et al. 1996), centered at $(l, b) \sim (205°, 10°)$, is thought to be an ancient supernova remnant at a distance of $\sim$ 200 pc. Also visible on this map are the Cygnus Loop supernova remnant at $(l, b) \sim (74°, -9°)$, and the Vela supernova remnant $(l, b) \sim (263°, -3°)$.

In the 1/4 keV band map, we see that there is emission from all directions, even the Galactic plane where we cannot see farther than $\sim$ 100 pc. This implies that there is some amount of very local emission. We know from interstellar absorption studies (Sfeir et al. 1999) that there is locally a deficiency of neutral material, the local cavity, so inside this local cavity is the natural place to find this local X-ray emission, the Local Bubble. Then there is the question of the bright regions at high Galactic latitudes: are they extensions of the Local Bubble, or are they due to halo or more distant emission shining into the local cavity?

A number of shadowing experiments have been done with *ROSAT*, in which the X-ray telescope was pointed towards a high latitude H I or molecular cloud and the decrease in X-ray brightness seen toward the cloud was used to constrain foreground and background X-ray emission. One of my favorite shadowing papers is the Snowden et al. (1994) *ROSAT* observation towards a 300 deg^2 region in Ursa Major around the direction of the lowest neutral hydrogen column density on the sky, the Lockman Window at $(l, b) \sim (150°, 52°)$. In the 21-cm map of that paper, neutral hydrogen clouds of column density $\sim$ 3 x 10^{20} cm^{-2} can be seen around $(l, b) \sim (136°, 53°)$ near the Window where the $N_{\rm H}$ drops as low as 0.5 x 10^{20} cm^{-2}. The distance to these clouds has been determined by Benjamin et al. (1996) to be $\sim$ 350 pc. The corresponding *ROSAT* 1/4 keV band X-ray map has the H I contours overlaid. We see X-ray minima on the face of the clouds providing a measure of the Local Bubble contribution in this direction: more than twice as bright as in the Galactic plane, but only 70% of the total 1/4 keV band emission in this direction.

We also see brighter X-ray emission in directions of lower $N_{\rm H}$ providing a measure of the 1/4 keV halo emission. We note the lack of detailed anticorrelation between the H I and the X-ray emission, indicating that the 1/4 keV halo emission is patchy on scales of 1°. In Draco, roughly 30°away, we see somewhat less bright emission from the Local Bubble, and much brighter 1/4 keV halo emission (Burrows & Mendenhall 1991; Snowden et al. 1991).

But not all clouds give 1/4 keV band shadows. MBM 12 is a dense low latitude cloud at a distance of 90 pc, located just in front of the larger Taurus-Auriga dark cloud complex. It shows little or no 1/4 keV shadow (Snowden, McCammon, & Verter 1993), which is consistent with its being at the edge of the Local Bubble, but

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it has a definite 3/4 keV shadow that is consistent with little or none ($< 20\%$) of the 3/4 keV band emission arising from within the Local Bubble.

Figures 2 and 3 in Sanders (1995) give views of the local solar neighborhood from within the plane of the Galaxy and from the north Galactic pole, showing the Sun within the local cavity, filled with the Local Bubble, the nearby Sco-Cen bubble, MBM 12 within the local cavity and the Taurus cloud beyond, the UMa lines of sight, the Eridanus superbubble, and the Monogem ring.

1.2. *The 3/4 keV Band*

At 3/4 keV we again see the Cygnus Loop and Vela supernova remnants and the Eridanus superbubble. The Loop I emission is more pronounced, but towards the direction $(l, b) \sim (0°, 0°)$ much of the emission is likely from the Galactic Bulge. In this band, we now see the Large Magellanic Cloud and the so-called Cygnus Superbubble. We also see clear signs of absorption both along the Galactic plane from galactic longitude $\sim 330°$ through the Galactic center to almost longitude 90°, and toward the Taurus-Auriga cloud complex in the Galactic anti-center direction.

The patchy halo emission seen in 1/4 keV is not seen at 3/4 keV, but rather at high latitudes we see smooth, nearly isotropic emission with few features. The origin of the 3/4 keV band flux is still a mystery. Roughly half of the total high latitude diffuse emission has been resolved into point sources that are almost entirely AGNs (Hasinger et al. 1993). Galactic stars may contribute as much as 10% of the apparently diffuse flux (Schmitt & Snowden 1990). The Local Bubble may contribute as much as 30% if the MBM 12 3/4 keV band upper limit on the local emision scales with the 1/4 keV band local count rate. An appreciable fraction appears to be coming from a smooth 3/4 keV halo that is distinct from the patchy 3/4 keV band halo (Wang 1998). A related mystery is why does the competition between the extragalactic and halo components that dominate at high Galactic latitudes and the Galactic components that dominate at low Galactic latitudes not produce a feature somewhere on the map? Why does the stellar and local bubble emission in the plane so exactly fill in the extragalactic emission that is absorbed in the plane?

Returning to the Bulge, Park et al. (1997, 1998) have presented evidence for an X-ray emitting Galactic Bulge using shadows cast by molecular clouds at distances greater than 3 kpc along several lines of sight around $(l, b) \sim (10°, 0°)$ and $(l, b) \sim (25°, 0°)$. Almy et al. (2000) have found similar results toward a molecular cloud ~ 2 kpc away toward $(l, b) \sim (337°, 4°)$. Snowden et al. (1997) have modeled the Bulge as a cylindrical emission region 5 kpc in radius with a 1.9 kpc scale height and with all of the $N_{\rm H}$ along the line of sight between us and the emission region. Their Figure 12 shows a plot of a cut through this region along Galactic longitude 335° for both the 3/4 keV band and the 1.5 keV band. At all points along the cut, the data lie on or above the model, with the excess emission attributed to the Loop I superbubble along the same line of sight. The Bulge surface brightnesses found by these three groups are consistent with one another to within roughly 30%.

1.3. *The 1.5 keV Band*

As we turn to the 1.5 keV band map, we see that the Galactic features are relatively weaker, and Hasinger et al. (1998) find that the fraction of the background contributed by AGNs is in the 70–80% range. More distant and hotter Galactic gas is not easily studied using *ROSAT* because of its limited high energy response.

Both *ASCA* (Kaneda et al. 1997) and *XTE* (Valinia & Marshall 1998) have observed the Galactic ridge, a very narrow strip of enhanced harder X-ray emission within 1° of the Galactic plane towards the inner 60° of the Galaxy. Both groups discuss this emission as arising from a population of young supernova remnants, but are not able to explain all features of the data satisfactorily. There seem to be two different Galactic ridge components, with different scale heights as well as different temperatures. Valinia & Marshall (1998) use Raymond & Smith models and obtain temperatures $\sim 3 \times 10^7$ K for the ridge plasma. Kaneda et al. (1997) use two NEI plasmas to fit the ASCA data, one plasma with $kT \sim 0.8$ keV and far from equilibrium, and the other plasma having $kT \sim 7$ keV but close to equilibrium.

The hottest diffuse gas seems to be within 0.5° of the Galactic center where Maeda (1998) used *ASCA* data to find plasma temperatures in the range of $10^7 - 10^8$ K.

2. SPECTRAL DATA

On the subject of temperature, what do we know about the temperature, composition, or state of equilibrium of the plasmas in the Local Bubble and the Galactic halo? Not all that much, really. Using band ratios from the *ROSAT* all sky survey and from University of Wisconsin sounding rockets, and using pulse height fits to UW, *ROSAT*, or *ASCA* data typically give temperatures $\sim 10^6$ K for the Local Bubble and the 1/4 keV halo, with some hints of low abundances of Fe (Bloch et al. 1990). For the 3/4 keV band, typical temperatures are $10^{6.4-6.5}$ K, and for the Galactic Bulge both Park et al. (1997) and Snowden et al. (1997) found $T \sim 10^{6.6-6.7}$ K. To get higher spectral resolution, we turn to two other instruments, the Diffuse X-ray Spectrometer (DXS) and the X-ray Quantum Calorimeter (XQC).

2.1. *Diffuse X-Ray Spectrometer*

DXS is a Bragg crystal spectrometer that flew once on the Space Shuttle and was sensitive over the energy range 150–284 eV, essentially the 1/4 keV band, with energy resolution that varied from 5–17 eV over that range. During its flight, it scanned along the Galactic plane in the longitude interval $150° < l < 300°$. Sanders et al. (1998) give a brief description of the instrument and its calibration.

Figure 3 of Sanders et al. (1998) shows the DXS data from the interval $220° < l < 250°$ along the Galactic plane (the Puppis region), displayed as a function of energy. In this direction, the X-rays that we detect should be X-rays of Local Bubble origin almost entirely. The intensity of the DXS data is in good agreement with that measured in this direction by *ROSAT* and by the Wisconsin rocket survey. The spectrum shows lines and line blends that indicate that its origin is thermal, but the spectrum is not in agreement with the predictions of a single-temperature plasma in collisional equilibrium, independent of whether the model is Raymond & Smith or MekaL. As discussed in more detail in Sanders et al. (1998), the best fit that was obtained using standard equilibrium models was a modified Raymond & Smith, using line data calculated by Liedahl, with the elemental abundances allowed to float. This fit required reducing the abundances of Fe, Si, and S by factors of 2–3, but the result was still not a good fit (reduced chi-square was ~ 2). Several NEI models were also tried, but their fits were no better. A lot of work remains to be done in analyzing these data, in particular not doing global model fitting, but focusing on individual ions and their lines.

2.2. *The X-ray Quantum Calorimeter*

The XQC sounding rocket detector is a micro-calorimeter—a device that is small enough (~ 1 mm^2) and cold enough (~ 60 mK) that its heat capacity is so small that the energy of one X-ray photon raises its temperature a measurable amount. This process can be made highly repeatable so that very good energy resolution, a few eV, is obtainable. The detectors flown on the most recent University of Wisconsin/Goddard Space Flight Center sounding rocket flight achieved 4–5 eV resolution in the laboratory and ~ 8 eV resolution in flight.

The data in the 0.1–1 keV energy range from that most recent XQC flight are shown in the first figure of Stahle, McCammon, & Irwin (1999). The field of view was 1 sr, centered on $(l, b) \sim (90°, 60°)$. The intensity of the XQC data is consistent with the *ROSAT* and UW rocket survey data from this part of the sky. In the spectrum, the lines of O VII at 560–574 eV and O VIII at 653 eV are clearly visible. Just as clearly, the lines of Fe XVII and Fe XV in the energy range between 727–827 eV are not seen. This is consistent with the *ASCA* results of Gendreau et al. (1995) and Chen, Fabian, & Gendreau (1997), but not with the models having a thermal component at $T \sim 3 \times 10^6$ K used by the Wisconsin group to account for the measured flux in their 3/4 keV band (M band). Either the temperature of this component is lower than we thought previously, or the abundance of iron in the emitting plasma is $< 25\%$ of solar.

The spectrum also does not show a strong line or line complex due to Fe IX, Fe X, Fe XI at ~ 70 eV as most models do. This might be an indication of reduced Fe abundance in the Local Bubble, but it is too early to be sure. The data in the Stahle et al. (1999) spectrum are not reliable below about 200 eV due to data reduction issues that are still being worked on. Other features of the spectrum are a probable C VI line at 367 eV and possibly emission from N VII in the 450–550 eV region.

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Clearly there is a lot of work to be done yet to understand and interpret these data. Complications are the large field of view, which makes it more difficult to separate Galactic and extragalactic contributions, and the small number of counts. But the potential for making progress towards understanding the emission from hot gas in the Galaxy in the 0.1–1 keV band through analysis of these data is very high.

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W. T. Sanders: Department of Physics, University of Wisconsin-Madison, 1150 University Avenue, Madison, WI 53706, USA (sanders@wisp.physics.wisc.edu).