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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
Editors: Jane Arthur, Nancy Brickhouse, & José Franco

ON DETERMINING THE SOURCES OF HOT GAS IN THE HALO

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RESUMEN

El gas caliente sobre el disco galáctico representa un problema importante e interesante. ¿Podría este gas haber sido lanzado desde el disco por burbujas calientes, provenir de fuera de la Galaxia o ser calentado *in situ*? Cada una de estas posibilidades tiene consecuencias importantes para la evolución de la Galaxia, por lo que es necesario tener mejores pruebas. Discutimos varios modelos sobre el origen del gas caliente, su historial de ionización y su apariencia espectral, así como un esquema que permita diferenciar los diferentes modelos con los datos de rayos-X y lejano UV que colectarán los nuevos observatorios.

ABSTRACT

The hot gas above the Galactic Disk provides an interesting and important puzzle. Could this gas have been advected from hot bubbles formed in the disk, dropped upon the Galaxy from above, or heated *in situ*? Each of these possibilities has important ramifications for the functioning of the Galaxy, magnifying the need for better tests. In this paper, several theoretical models for hot gas in the halo, their ionization history, and spectral appearances will be discussed, along with a scheme for using the emerging set of soft X-ray and far ultraviolet observatories to distinguish between classes of models.

Key Words: **GALAXY: HALO — HYDRODYNAMICS — ISM: STRUCTURE — X-RAYS: ISM**

1. EXISTING OBSERVATIONS OF HIGHLY IONIZED GAS IN THE LOWER HALO

If only X-ray photons would arrive at earth with return addresses so that we would know where they originated. They do not. So, the current approach is to determine if high z clouds block out some of the X-ray flux. If so, then the fraction originating beyond the clouds can be estimated. With this method, Snowden et al. (1998) determined that the (de-absorbed) 1/4 keV X-ray surface brightness of the southern halo averages about 400×10^{-6} *ROSAT* R1 + R2 counts s^{-1} arcmin^{-2}, after subtracting the extragalactic component. In Snowden's maps, the southern sky has a dim, mottled appearance, enlivened by a couple of bright crescents. It is quiescent compared with the north, which has a very bright arc (Loop I), several somewhat bright regions, and a dim, mottled background. Because the north is contaminated by features such as Loop I, this paper will take the south as the fiducial.

Very recently, Kuntz & Snowden (2000) examined the spectra for the possibility that it might have one or two, distinct temperature components, finding that it has a 1.2×10^6 K component whose strength varies significantly across the sky as well as a 3.0×10^6 K component whose strength may vary slowly across the sky. These temperatures are actually "color temperatures", the temperatures of the emitting plasmas found under the assumption that the plasmas are in collisional ionizational equilibrium. These two color temperature components are thought to be disjoint, and it is the 1.2×10^6 K component which appears mostly in the 1/4 keV band, also called the C band for some detectors, and which is relevant to this paper.

In order to put the strength of the halo component in context with another large, diffuse X-ray feature, it will be compared with the Local Bubble of hot gas surrounding the solar neighborhood. The Local Bubble's surface brightness is ~ 250 to 820×10^{-6} *ROSAT* R1 + R2 counts s^{-1} arcmin^{-2}. Thus, on average, the deabsorbed surface brightness of the southern half of the Galactic halo is about 75% as bright as the Local

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Bubble. Furthermore, the Galactic halo and the Local Bubble have similar color temperatures.

The oxygen atoms in the soft X-ray emitting gas are thought to be in their hydrogen-like and helium-like ionization states. The next step down, the lithium-like ion of oxygen, or O^{+5}, is also seen in the halo. Making the standard assumption of collisional ionizational equilibrium, this gas should be most prevalent in 3×10^5 K gas. This ion is identified via its absorption and emission of ultraviolet 1032 and 1038 Å light. By compiling the *Copernicus* and ORFEUS absorption observations, and subtracting the estimated Local Bubble contribution, the average vertical column density of O^{+5} ions beyond the Local Bubble and average exponential scale height have been found. They are 6.4×10^{13} O^{+5} ions cm^{-2} and ∼1100 to 1550 pc, respectively (Shelton 1998; 2000). The Far Ultraviolet Spectroscopic Explorer (*FUSE*) was launched in June of 1999. By the time that this proceedings is published, *FUSE* will have added absorption data to the dataset. *FUSE* may also establish better limits on the O^{+5} surface brightness as well as a better estimate of the Local Bubble surface brightness so that it might be subtracted from the high latitude total.

2. SELECTED EXPLANATIONS

Over the years, quite a few theoretical explanations have been considered. This section describes several theories, concentrating on supernova remnants, which were the topic of the original abstract.

2.1. *Supernova Remnants Born Above the Disk*

Supernova remnants (SNRs) born above the Galactic disk, provide a possible explanation for the current accumulation of observations. Simulations show that the expected population of SNRs above the disk provides approximately enough 1/4 keV X-rays to agree with the *ROSAT* PSPC observations and enough O^{+5}, and with the appropriate scale height and patchiness to agree with the O^{+5} column density observations (Shelton 1998; 1999). Another sort of testing can be done with the ionization history of the gas. Simulations of supernova remnants in low density media show that the remnants spend most of their lifetimes out of collisional-ionizational-equilibrium. For example, in a simulation using an explosion energy of 10^{51} ergs, ambient density of 10^{-2} cm^{-3}, and ambient effective magnetic field of 5×10^{-6} μG, the remnant's gas was extremely hot (10^7 to 10^8 K), but most of the metal atoms were in only moderately high ionization states until the cool shell formed behind the shockfront at a few $\times 10^5$ years. The emission spectrum produced by this underionized gas was plotted in Figure 20 of Shelton 1999. If this spectrum were to be observed with the *ROSAT* PSPC so that its "color temperature" could be calculated from the *ROSAT* PSPC R1 and R2 band ratio, the resulting color temperature would be only 1 or 2×10^6 K. Compared with the actual halo observations by the *ROSAT* PSPC, such a range is consistent, especially when the uncertainties are considered. Additional characteristics of this phase are that these remnants are very luminous and edged brightened in 1/4 keV X-ray photons. They are also very rich and edge brightened in O^{+5}, N^{+5}, and C^{+5}.

The ionization situation reverses around the time that the cool shell forms. The gas has been cooling by adiabatic expansion, thermal conduction, and radiation faster than the ions have been recombining, leaving the metal atoms in higher ionization states than they would be if the gas were in collisional ionizational equilibrium at the remnant's temperature. An example of the emission spectrum produced by such overionized gas is plotted in Figure 20 of Shelton 1999. If the spectrum were to be observed with the *ROSAT* PSPC, its color temperature would be about 10^6 K, consistent with that actually observed with the *ROSAT* PSPC. At later ages, the remnant produces a somewhat cooler color temperature. Other characteristics of the remnant are that the X-ray emission is now dim, but brightest nearest the centers of the projected remnant, and the O^{+5}, N^{+5}, and C^{+5} ions are now less common than in the younger remnants.

The old phase of evolution lasts roughly 10^2 times longer than the young phase. As a result, the older phase produces more 1/4 keV photons than the younger phase. The old SNRs would appear as a dim, mottled soft X-ray background covering much of the high latitude sky, while the young SNRs would appear as brighter crescents covering a tiny fraction of the sky.

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2.2. *Winds and Fountains, Turbulent Mixing, and Microflares*

Other explanations for the highly ionized gas above the Galactic Disk, include winds and fountains (Shapiro & Field 1976; Edgar & Chevalier 1986; MacLow & McCray 1988; Shapiro & Benjamin 1991), turbulent mixing layers (Slavin, Shull, & Begelman 1993), and magnetic reconnection microflares (Raymond 1992).

Microflares may occur when crossed magnetic field lines reconnect. During the process, some of the magnetic energy impulsively converts to heat. The affected localized regions increase in temperature much faster than their atoms can ionize, yielding hot, underioinized gas. These regions may cool somewhat faster than their ions can recombine, causing the gas to become overionized.

Turbulent mixing on the shearing interfaces between bodies of hot and warm gas transfers energy from the hot gas to the warm gas. The affected masses of recently heated, underionized gas are expected to be much larger than the masses of recently heated, overionized gas, thus the combined spectra may be dominated by that of the underionized gas.

Winds and fountains are the flow of hot, highly ionized gas from disk sources to the halo. The bases should be extremely hot and underionized, while the tops should be cool and overionized.

3. IONIZATION HISTORY AS A USEFUL DIAGNOSTIC

The theoretical hot regions can be regrouped in terms of their ionization history, with the "ionizing gas" category containing young supernova remnants, fountain columns, young microflares, and heated portions of turbulent mixing layers, the "recombining gas" category containing old supernova remnants, fountain tops, old microflares, and cooled portions of turbulent mixing layers. In addition, a "mixed or near equilibrium gas" category would exist and contain some parts of turbulent mixing layers and fountains, and some ages of supernova remnants and microflares.

When examining the soft X-ray spectra with a low energy resolution detector such as the *ROSAT* and only the 1/4 keV band, the standard approach is to use the R1 and R2 bands to determine the color temperature. Under these conditions, the ionization history information is too blurred and truncated to properly show itself. This situation is rapidly changing because the current generation of observatories, *Chandra*, *XMM*, and *AstroE*, have much finer energy resolution and bandpasses which better cover the gap between the 1/4 and 3/4 keV range. Much better observations of the soft X-ray spectrum may also be gotten from a high resolution calorimeter currently being flown on rocket flights and proposed for future missions (Sanders et al. 1997). Another emerging approach is to compare the soft X-ray spectra with O VI emission observations coming out of the *FUSE* mission.

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