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High velocity clouds interacting with galactic halo plasma as a source of X-ray emission

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Abstract. Several high velocity clouds (HVCs) are now known to be soft X-ray sources. In this paper we suggest that an interaction between the HVCs and the galactic halo is leading to plasma instabilities that generate energetic electrons which in turn generate X-ray emission. This process is essentially analogous to the interaction process between comets and non-magnetized planets with the solar wind which is also known to lead to the generation of X-rays. We show that for reasonable assumptions about the galactic halo magnetic field, the X-ray emission can be converted into an estimate of the mean galactic halo density at the position of the cloud. This provides a method for estimating the baryonic mass of the plasma halo provided that we can obtain a good estimate for the distance to the HVC.

1. Introduction

High velocity clouds (HVCs) were first discovered nearly forty years ago by Müller et al. [1]. They are H I structures which are observed to have radial velocities that deviate significantly from the well established galactic rotation pattern, typically by several hundred km s^{-1}. In the northern hemisphere these velocities are most often negative indicating that the gas is falling towards the plane of the galaxy. In many cases there are also intermediate velocity gas clouds (IVCs) and these also show negative velocities indicating infall. The distances to most HVCs remains uncertain, but loose distance limits are now becoming available for several HVC cloud complexes and these distances are consistent with a location in the galactic halo. This places them in a location that is very difficult to study with most 'normal' methods. In fact, the HVCs can be used as 'probes' for studying the environment and conditions in the halo—provided that the HVCs have some interaction with their surroundings. Ever since HVCs were first detected, in fact, it has been anticipated that they should interact with the gas in the galactic disk [2]. However, since there is now strong evidence that our galaxy is surrounded by a hot halo, an interaction between an HVC and this halo gas seems even more likely. Evidence for a hot galactic halo comes from studies of the soft X-ray background [3, 4], which shows evidence for a flattened and/or variable halo component with a log T of 1–1.6 $\times 10^6$ K. Furthermore, the detection of C IV towards five stars in the Large

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Magellanic Cloud (LMC) show that it too is surrounded by a hot corona/halo, which is also observed to be spatially variable [5].

Evidence that some high velocity clouds are, indeed, interacting with the galactic disk comes from the observation of intermediate velocity 'bridges' that are seen to connect HVCs with disk gas (see, for example, [6]). Another indication of an interaction can be deduced from the observation of soft X-ray enhancements close to several HVC cloud complexes—for example from cloud Complexes M and C [7].

2. Soft X-ray observations in the vicinity of HVC

The ROSAT X-ray satellite was launched in 1990 and very quickly established that the soft X-ray background in the $\frac{1}{4}$ keV X-ray band had both 'local' and 'distant' components. The local component was well known ('The local hot bubble' [LHB]). However, the observation of soft X-ray shadows from H I clouds [8] indicated that a substantial fraction of the emission was coming from distances beyond the clouds. These results clearly demonstrated that about 50% of the $\frac{1}{4}$ keV X-ray background originated more than 400 pc away in the galactic halo and beyond the LHB. As already discussed above, this gas is at a temperature of 1–1.6×10^6 K and it is distribution in a patchy fashion in the halo. This evidence is also supported by other observations in the ultraviolet (UV) and extreme ultraviolet (EUV) that show absorption lines of highly ionized carbon and nitrogen (C IV and N V) in the UV and oxygen (O VI) in the EUV towards halo, LMC stars, and distant active galaxies [9,10]. The N V indicates significant amounts of collisionally ionized gas at temperatures of around 2×10^5 K and O VI requires T of $\sim 3 \times 10^5$ K. In addition, the line widths, of the O VI absorption features are typically much wider than the expected thermal widths, indicating the requirement for a non-thermal line broadening mechanism [10]. The good imaging capabilities of the ROSAT PSPC and the recent completion of the Leiden–Dwingeloo H I 21 cm survey have allowed the search for enhanced soft X-ray emission in the vicinity of HVC cloud complexes.

2.1. HVC Complex M

HVC Complex M is roughly in the galactic anti-centre direction and at high (northern) galactic latitudes. It actually appears to lie at the 'top' of the long linear feature that is HVC Complex C (see the recent all-sky map in [11]). At higher spatial resolution, the curved arc of emission is seen to resolve into three or four components in the highest velocity interval [12]. An arc of material is also seen to connect the M Complex with the top of the C Complex. In some ways, the M Complex resembles a 'fish-hook' attached to the long filamentary C Complex 'line'. Herbstmeier et al. [12] took their radio data from the Leiden–Dwingeloo H I 21 cm survey and made maps with a $0.5^\circ \times 0.5^\circ$ grid resolution. Their soft X-ray data came from the ROSAT PSPC All-Sky survey.

On the combined $\frac{1}{4}$ keV soft X-ray and H I 21 cm maps of the M cloud Complex, the X-ray emission is seen to be situated 'within' the curved fish-hook of M cloud concentrations. It is possible that some foreground neutral hydrogen may be absorbing some fraction of the soft X-ray emission on the edge furthest away from the M Complex clouds, since the contour of intermediate and local H I very closely matches the profile of the soft X-ray emission. This is best seen in map 2-e of Herbstmeier et al. [12]. In what follows we will consider in detail the possible relationship between the soft X-ray and neutral hydrogen by detailed examination of

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the maps presented in [12], in particular Figs 2 (a)–(e). In Fig. 2(a), Herbstmeier et al. labelled parts of the M Complex M I, M II, M III and M IV. M I and M II form most of the 'top' of the M Complex and are clearly seen to 'contain' the soft X-ray emission—there is very little overlap between the two maps. If one then compares the soft X-ray profile with the intermediate velocity neutral hydrogen maps (2(b) and 2(c)) the pattern-match is less good, except for a 'finger' of hydrogen at $[l, b] \sim [180°, +60°]$. M III is basically parallel with M II and closer to the disk of the galaxy. This component in H I does appear to overlap with the bulk of the soft X-ray emission, but it is most likely to be further away than the X-ray emission since neutral hydrogen columns of several $\times 10^{19}$ cm^{-2} would certainly attenuate much of the soft X-ray emission. M IV is seen to be an individual feature that is once again closer to the galactic disk than M II and M III. It is also co-spatial with the intermediate and positive velocity H I that seems to mark the lower boundary of the soft X-ray emission. Again, at this boundary there is seen to be very little overlap between the two emission components.

So, in conclusion, on the boundaries of the soft X-ray emission that are parallel to the galactic disk, the neutral hydrogen at high and intermediate velocities is seen to be a very good match, suggesting the possibility that the M I, M II and M IV components are shadowing or absorbing the soft X-ray emission. On the other hand, there does appear to be some positional correlation with the M III cloud component. Unfortunately, the exact three-dimensional structure of the whole M Complex is unknown to confirm whether such a configuration is correct. Herbstmeier et al. [12] reached essentially the same conclusions from their more detailed analysis of the two data sets.

2.2. HVC Complex C

HVC Complex C was first discovered in 1966 [13], and is a very large feature. On the most recent maps [11, 12] it can be seen that the C Complex breaks down to a series of long filaments that do contain substructure within. The neutral hydrogen has a typical velocity of -130 km s^{-1} relative to the local standard of rest (LSR). The detailed comparison between the ROSAT $\frac{1}{4}$ keV soft X-ray and H I 21 cm maps are presented in [14]. The ROSAT soft X-ray maps presented by Kerp et al. [14] show three regions of enhanced emission. One of these regions is coincident with a density enhancement in the 'outside' filament of Complex C—which is referred to as HVC$90.5 + 42.5 - 130$ (corresponding to its galactic location and local standard of rest [LSR] velocity). This feature also shows X-ray emission that extends out perpendicular to the filament. The other two regions of enhanced emission appear to lie in 'notches' on the edge of the C Complex filament—one at about $[l, b] = [100°, +52°]$ and the second one at $[l, b] = [110°, +59$–$60°]$. Kerp et al. [14] state that all three soft X-ray enhancements correspond to points on the C filament that have intermediate velocity 'bridges' connecting the HVC material with the galactic disk material. This, they argue, is positive proof that the HVC is impacting and interacting with the intermediate velocity and galactic disk gas. They also suggest that the diagonal gradient in velocity across the filament is another sign that interaction is taking place—the interaction would then be causing the deceleration. So, where there is a clear indication of interaction between the HVC and the galactic halo gas, there is also soft X-ray emission present.

All the positions in Cloud Complexes M and C mentioned above as sources of soft X-ray emission also have significant column densities of O VI [10].

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3. X-ray generation mechanism

The X-ray generation mechanism in the cloud halo is not fully understood. In this section we outline one possible scenario based on plasma streaming instabilities. The particular instability invoked is the modified two stream instability (MTSI) resulting in the generation of lower-hybrid turbulence. These waves are suitable for accelerating electrons to the keV energy range (in multiple interactions). A similar model has been used to explain X-ray emission from the interaction of the solar wind with cometary atmospheres and planetary exospheres such as Mars and Venus [15, 16].

3.1. Electron acceleration by the lower-hybrid waves

Resonant interaction between lower-hybrid waves and electrons can result in field aligned electron acceleration. These waves are most probably excited by the modified two stream instability resulting in the halo region from the interaction between the galactic halo plasma and photoionized HVC ions, forming under the action of $E \times B$ pick-up a crossed field monoenergetic ion ring in the plasma. This interaction drives the modified two stream instability described by the following dispersion relation [16],

$$\frac{\omega_{\mathrm{lh}}^2}{\omega^2} + \frac{\omega_{\mathrm{ce}}^2}{\omega^2}\frac{k_\parallel^2}{k^2 + \omega_{\mathrm{pe}}^2/c^2} + 8\pi^2 i \int dv_\parallel \int_{\omega/k_\perp}^{\infty} dv_\perp \frac{\partial f_{\mathrm{i}}/\partial v_\perp}{\sqrt{k_\perp^2 v_\perp^2 - \omega^2}} = 1 + \frac{\omega_{\mathrm{pe}}^2}{k^2 c^2}, \quad (1)$$

where $f_{\mathrm{i}}(v_\perp, v_\parallel)$ is the distribution function of the HVC ions. We assumed that as a result of ion gyration in the extended galactic magnetic field, particles are completely mixed over phase of rotation and establish a gyrotropic distribution $f(v_\perp, v_\parallel)$, contrary to the case of non-gyrotropic plane beam distribution. The instability excites lower-hybrid waves having the following dispersion law

$$\omega^2 = \frac{\omega_{\mathrm{lh}}^2(1 + \beta/2k^2\rho^2) + \omega_{\mathrm{ce}}^2(k_\parallel^2/k^2)}{(1 + \beta/2k^2\rho^2)^2} \quad (2)$$

where $\beta = 8\pi n_{\mathrm{o}} T_{\mathrm{p}}/B_{\mathrm{o}}^2$ is the ratio of the plasma kinetic pressure in the galactic halo to the magnetic pressure, $\rho = \sqrt{(T_{\mathrm{p}}/m_{\mathrm{e}})}(1/\omega_{\mathrm{ce}})$ is the electron gyroradius calculated with the proton temperature.

The integral over $v_\perp$ on the right-hand side of equation (1) can be easily calculated, giving the following expression for the growth rate [15, 16],

$$\gamma = \frac{n_{\mathrm{i}}}{2n_{\mathrm{o}}}\frac{m_{\mathrm{p}}}{m_{\mathrm{i}}}\frac{\omega^2\omega_{\mathrm{lh}}^2}{k^3 v_\perp^3}\frac{1}{1 + (\beta/2l^2\rho^2)}. \quad (3)$$

In order for the instability to be viable it needs to develop on a distance scale of something like

$$r \approx 10\frac{v_{\mathrm{HVC}}}{\gamma} \quad (4)$$

which must also be shorter than the physical dimensions of the interaction region.

The wave spectrum is centred on the average energy ε_{e}, which can be obtained from energy balance between the ions' mass loading the solar wind and the accelerated electrons

$$\alpha n_{\mathrm{i}} m_{\mathrm{i}} u^3 \approx n_{\mathrm{Te}} \varepsilon_{\mathrm{e}} \left(\frac{\varepsilon_{\mathrm{e}}}{m_{\mathrm{e}}}\right)^{1/2}, \quad (5)$$

where α is the transformation efficiency from ions to electrons, their density n_{Te}

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can be estimated by balancing the growth rate of the instability initiated by pickup ions with Landau damping due to hot electrons

$$\gamma_{\rm i} + \gamma_{\rm e} \sim \frac{\partial f_{\rm i}}{\partial v} + \frac{m_{\rm i}}{m_{\rm e}} \frac{\partial f_{\rm e}}{\partial v_{\|}} \approx 0. \tag{6}$$

This equation can be rewritten as

$$\frac{n_{\rm Te}}{\varepsilon_{\rm e}} \approx \frac{n_{\rm i}}{m_{\rm i} u^2}, \tag{7}$$

and together with the above equation for the energy balance it gives the following estimations for the average energy $\varepsilon_{\rm e}$ of the accelerated electrons and their number density [15]:

$$\varepsilon_{\rm e} \approx \alpha^{2/5} \left(\frac{m_{\rm e}}{m_{\rm i}} \right)^{1/5} m_{\rm i} u^2, \tag{8}$$

$$n_{\rm Te} \approx n_{\rm i} \alpha^{2/5} \left(\frac{m_{\rm e}}{m_{\rm i}} \right)^{1/5}. \tag{9}$$

Noting the weak dependence of the result from the energy transformation coefficient, α, we can use the value of $\alpha \sim 0.1$. Then near the HVC 'cloudopause' where the ion energy $m_{\rm i} u^2 \sim 150$ eV, we can obtain the typical electron energy $\varepsilon_{\rm e} \sim 30$ eV, and the density of the accelerated electrons $n_{\rm Te} \sim 0.1$ cm^{-3}. Even this simple estimate demonstrates the large efficiency of electron acceleration.

Below we shall use the calculations of the electron flux in the analysis of X-ray emission produced by the impact of energetic electrons with the cometary atmosphere. Radiation is a combination of the bremsstrahlung emission produced by electron neutral collisions and inner shell radiation from the collisionally excited oxygen atoms.

For electron neutral bremsstrahlung the power radiated by one electron in collisions with neutrals in 1 cm^3 is given by

$$P = \int \hbar \omega n_N \, d\sigma(\omega). \tag{10}$$

Here $\hbar$ is Planck's constant divided on 2π, ω is the radiation frequency, n_N is the number density of the hydrogen cloud, and $d\sigma(\omega)$ is the differential cross-section of bremsstrahlung given by the following formulae [17].

$$d\sigma(\omega) = \frac{16 Z^2 e^2 c}{h v} r_{\rm o}^2 \ln\left(\frac{m_{\rm e} v^2}{2\hbar\omega} \right) \frac{d\omega}{\omega}, \tag{11}$$

where $r_{\rm o} = e^2/m_{\rm e}c^2$ is the classical electron radius and Ze is the charge of the nucleus of the neutral molecule. The total power radiated per unit volume can be obtained from (67) by multiplying it by $f_{\rm e}\, dv$ and integrating over particle velocities with the distribution function obtained in the first part of the section.

To calculate the power spectral density of the radiation, integration must be performed over all energies contributing to the radiation of photons with frequency ω, i.e. over energies satisfying the condition $\varepsilon = m_{\rm e} v^2/2 \geq h\omega$. Finally, to determine the radiation from the shell distance R and thickness ΔR of the interaction region it is necessary to multiply the result by the shell volume $2\pi R^2 \Delta R$. The final result

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for the total radiated power spectral density is

$$dL_{\mathrm{BR}}(\omega) = \frac{16\pi}{3} n_N R^2 \Delta R Z^2 e^2 c r_{\mathrm{o}}^2 \int_{h\omega}^{\infty} \frac{d\varepsilon}{\varepsilon} f(\varepsilon) \ln\left(\frac{\varepsilon}{h\omega}\right) d\omega. \tag{12}$$

It follows from the solution of the electron diffusion equation described previously that the main input into bremmstrahlung radiation comes from the plateau region of the distribution function where $f_{\mathrm{e}} \approx n_{T\mathrm{e}/\sqrt{2\varepsilon_*/m_{\mathrm{e}}}}$ for $\varepsilon \leq \varepsilon_*$. Substituting numerical values for all constants in the right-hand side of (12) and using in the integral the plateau-like distribution function of electrons it is possible to derive the following expression for the spectral density of bremmstrahlung radiation

$$dL_{\mathrm{BR}}(\omega) = 4.9 \times 10^{-41} Z^2 \Delta R 2\pi R^2 \frac{n_N n_{T\mathrm{e}}}{\sqrt{\varepsilon_*(\mathrm{eV})}} \ln\left(\frac{\varepsilon_*}{h\omega}\right) d\omega \text{ erg s}^{-1}. \tag{13}$$

The total X-ray luminosity due to Bremsstrahlung can be easily obtained from (13) by integrating over all frequencies $\omega \leq \varepsilon_*/h$ and is given by the following expression

$$L_{\mathrm{BR}} = 10^{-24} \Delta R R^2 n_N n_{T\mathrm{e}} \sqrt{\varepsilon_*(\mathrm{eV})} \text{ erg s}^{-1}. \tag{14}$$

In addition to bremmstrahlung radiation producing the continuous spectrum, there is also the K shell line radiation from the partially ionized and neutral oxygen, carbon or other heavy cloud ions which will make up the low temperature plasma halo, whose bound electrons are excited by the inelastic collisions with suprathermal electrons. The bound electron quickly de-excite and re-radiate the energy it obtained in the collision. This type of radiation is known in fusion as 'impurity' radiation, and it is an important source of energy loss in fusion reactors [18–20].

The detailed numerical analysis of the 'impurity' radiation has been done by Jensen et al. [20]. However, the basic physics of radiation can be explained using the simple picture proposed by Dawson [21], where he assumed that the cross-section of the line radiation is determined by inelastic Coulomb collisions between free and bound electrons with a small impact parameter, thereby leading to the relatively large angle scattering of the colliding electrons. The Coulomb logarithm which usually increases the cross-section of electron–electron collisions by a factor of 10–20, due to a result of distant collisions, is in this case of order unity. Note that line radiation is a strong function of Z, for example X-ray radiation from oxygen is from K shell radiation in the energy range 500–800 eV. Jensen et al. [20] calculate the photon energy production rate for oxygen atoms and show it as a function of electron energy. The X-ray energy production rate based on the physical picture of Shapiro et al. [16] can be represented by the following approximate formulae

$$P = 5 \times 10^{-18} \Lambda \frac{n_N n_{\mathrm{e}}}{\sqrt{\varepsilon_{\mathrm{e}}}} \text{ erg cm}^{-3} \text{ s}^{-1}. \tag{15}$$

Here n_{e} is the density of the energetic electrons capable of producing line emission, and Λ is a numerical factor of order 0.1 for oxygen atoms. Since the radiation is produced mainly inside the cloud bowshock in the so-called cloudopause region, where the galactic halo is strongly compressed to a density $n_{\mathrm{o}} \approx 10^2$ cm^{-3}, it follows from the quasilinear calculations that approximately 10% of these electrons are accelerated up to energies of several hundred eV, needed to produce line radiation, we can assume that $n_{\mathrm{e}} \approx 10$ cm^{-3}. Then, using for the photon production rate expression (11), and integrating over the whole radiating volume and over all energies

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inside the photon line spectrum, we can write the following expression for the total radiated power in line emission

$$L_{\text{line}} = 3 \times 10^{-17} \Lambda R^2 \Delta R \frac{n_N n_{\text{Te}}}{\sqrt{\varepsilon_*}} \text{ erg s}^{-1}. \quad (16)$$

From (14) and (16) and knowing the X-ray intensity and estimating the distance R and thickness ΔR, we can estimate the density of the halo plasma and thus infer a mass for the galactic halo. This would be an extremely important result, since it will provide an insight into the baryonic mass of the Galaxy.

4. Conclusions

We have identified a possible mechanism to explain the X-ray emission from high velocity clouds interacting with the galactic halo plasma. The mechanism relies on the velocity of the ultra cold hydrogen cloud (which is around 150 km s^{-1}). If we can then add a knowledge of the distance to these clouds and use the present observations to infer the shell thickness of the interaction region then it will be possible to 'invert' the X-ray production equation and derive the halo density directly from the observations. This would then be a direct way of measuring the baryonic mass of the halo and hence of the whole galaxy.

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paper starts with a dedication to Professor Lyman Spitzer Jr who was the first person to propose that the galaxy could have a hot halo in a classic paper (1956 *Astrophys. J.* **124**, 20).

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