WARM GAS AND IONIZING PHOTONS IN THE LOCAL GROUP

PHILIP R. MALONEY and J. BLAND-HAWTHORN

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ABSTRACT

Several lines of argument suggest that a large fraction of the baryons in the universe may be in the form of warm ($T \approx 10^5$–$10^7$ K) gas. In particular, loose groups of galaxies may contain substantial reservoirs of such gas. Observations of the cosmic microwave background by COBE place only weak constraints on such an intragroup medium within the Local Group. The idea of a Local Group corona dates back at least 40 years (Kahn & Woltjer). Here we show that gas at $T \approx (2–3) \times 10^6$ K (the approximate virial temperature of the Local Group)—extremely difficult to observe directly—can in principle radiate a large enough flux of ionizing photons to produce detectable H$\alpha$ emission from embedded neutral clouds. However, additional constraints on the corona—the most stringent being pulsar dispersion measures toward the Magellanic Clouds, and the timing mass—rule out an intragroup medium whose ionizing flux dominates over the cosmic background or the major Local Group galaxies. A cosmologically significant coronal gas mass could remain invisible to H$\alpha$ observations. More massive galaxy groups could contain extensive coronae which are important for the baryon mass and produce a strong, local ionizing flux.

Subject headings: cosmic microwave background — diffuse radiation — intergalactic medium — Local Group

1. INTRODUCTION

The standard big bang cosmological model makes remarkably precise predictions for the abundance of baryons in the universe; in terms of the critical density parameter $\Omega$, the prediction is $\Omega = 0.068 \pm 0.012$ $h^2$, where we take the present-day Hubble constant to be $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$ (e.g., Olive, Steigman, & Walker 1991; Schramm & Turner 1998). An inventory of baryons observed at high redshift ($z \approx 2–3$), chiefly in the form of the low-column density Lyman–$\alpha$ forest clouds, gives an estimate of $\Omega_b$, which, although subject to substantial, systematic uncertainties, is in reasonable agreement with the standard prediction of big bang nucleosynthesis (see the summary in Fukugita, Hogan, & Peebles 1998). However, as has been noted repeatedly (e.g., Persic & Salucci 1992; Fukugita et al. 1998), at $z \approx 0$ only a small fraction of the expected number of baryons has been observed, suggesting that there is a substantial, even dominant reservoir of baryons which has not yet been characterized.

A plausible suggestion for one reservoir of baryons is that loose groups of galaxies contain substantial masses of warm ($T < 10^7$ K) ionized gas, an idea which appears to have originated with Kahn & Woltjer (1959; see also Oort 1970; Hunt & Sciami 1972). X-ray observations of poor groups of galaxies frequently detect intragroup gas at $T \approx 1$ keV (e.g., Pildis, Bregman, & Evrard 1995; Mulchaey et al. 1996). In general, only groups dominated by ellipticals are detected; spiral-rich groups tend to show only emission from individual galaxies. Although this may be due to the absence of gas in such groups, it is also plausible that the gas has not been seen because its temperature is too low: the velocity dispersions characterizing groups dominated by spiral galaxies are significantly smaller than those of compact, elliptical-dominated groups and imply temperatures $T \sim 0.2–0.3$ keV (Mulchaey et al. 1996), making detection even at relatively soft X-ray wavelengths very difficult.

Most recently, Blitz et al. (1998) have suggested that the majority of high-velocity clouds (HVCs; for a review, see Wakker & van Woerden 1997) are not associated with the Galactic ISM, but represent remnants of the formation of the Local Group (LG), as material continues to fall into the LG potential. In this scenario, some fraction of these infalling clouds will collide in the vicinity of the LG barycenter and shock up to the virial temperature, $T \sim 2 \times 10^7$ K, producing a warm intragroup medium.

In this Letter, we explore the possibility that the Local Group contains such a reservoir of warm ionized gas. In particular, we examine whether significant constraints can be placed on the amount of gas through the detection of recombination lines from neutral gas within the Local Group. In the next section we briefly recapitulate the existing constraints on such an intragroup medium, and in § 3 we estimate the flux of ionizing photons. Section 4 discusses the implications and additional constraints which can be imposed, in particular, mass flux due to cooling and the timing mass of the Local Group.

2. COBE AND X-RAY CONSTRAINTS ON LOCAL GROUP GAS

Suto et al. (1996) suggested that a gaseous LG halo could significantly influence the CMB quadrupole moment observed by COBE. Assume the Local Group contains an isothermal plasma at temperature $T_e$ whose electron number density is (for core density $n_e$ and core radius $r_0$)

$$n_e(r) = n_0 \frac{r_0^2}{r^2 + r_0^2} \text{ cm}^{-3},$$

i.e., the nonsingular isothermal sphere. Since we allow $r_0$ as well as $n_e$ to vary, the parameterization of equation (1) includes density distributions ranging from $n_e \propto r^{-2}$ to $n_e \propto r^{-4}$.

As in Suto et al. (1996), we calculate the resulting Sunyaev-Zeldovich temperature decrement as a function of angle, expand in spherical harmonics, and average over the sky to obtain the monopole and quadrupole anisotropies.

The COBE FIRAS data (Fixsen et al. 1996) imply that the Compton $y$-parameter $|y| = T_e n_e/2 < 1.5 \times 10^{-5}$ (95% CL),

1 Center for Astrophysics and Space Astronomy, University of Colorado, Boulder, CO 80309-0389; maloney@casa.colorado.edu.

2 Anglo-Australian Observatory, P. O. Box 296, Epping, NSW 2121, Australia; jbh@aaoepp.aao.gov.au.
the product \( n_i r_0 T_{\text{eV}} \) in a LG corona is typical of that seen in more compact groups, merely at lower temperature, the mass in baryons can still be very substantial: for the density distribution (1), scaling \( n_i r_0 T_{\text{eV}} \) to \( 10^5 \) cm\(^{-3}\), the mass inside radius \( r \) is approximately (assuming \( r f_0 \approx \) a few)

\[
M(r) \approx 7 \times 10^{11} \left( \frac{r_0}{100 \text{ kpc}} \right)^2 \left( \frac{r}{r_0} \right) \left( \frac{n_i r_0 T_{\text{eV}}}{10^{20} \text{ cm}^{-2}} \right) \left( \frac{T_{\text{eV}}}{0.2} \right)^{-1} M_\odot;
\]

(4)

this could be a substantial fraction of the mass of the Local Group (see § 4).

Direct detection of emission from gas at such temperatures is exceedingly difficult. Using deep ROSAT observations, Wang & McCray (1993, hereafter WM) find evidence for a diffuse thermal component with \( T_{\text{eV}} \sim 0.2 \) and \( n_i \sim 1 \times 10^{2} \times 10^{0.5} \) cm\(^{-3}\) (assuming primordial gas) where \( x_{\text{He}} \) is the line-of-sight depth within the emitting gas in kiloparsecs. In the next section we consider an indirect method of detection: the recombination radiation from neutral gas embedded in the corona, due to the ionizing photon flux generated by the coronal gas.

3. IONIZING PHOTON FLUX FROM A LOCAL GROUP CORONA

We assume the density distribution (1). Approximating the surface of a cloud as a plane-parallel slab, the normally incident flux on the inner (facing \( r = 0 \)) cloud face is

\[
\phi(r) \approx \frac{\pi n_i^2 r_0}{(1 + r^2 f_0^2)^{1/2}} \xi \left[ 0.8 + 1.3(r f_0)^{1.35} \right] \text{ photons cm}^{-2} \text{ s}^{-1},
\]

(5)

where \( \xi \) is the frequency-integrated ionizing photon emissivity and the term in brackets is accurate to 10\% for \( 10^{-3} \leq r f_0 \leq 12 \). (For \( r f_0 \approx 2 \), the flux on the outer face of the cloud is insignificant.) To calculate \( \xi \), we have used the photoionization/shock code MAPPINGS (kindly provided by R. Sutherland).

Models have been calculated for metal abundances \( Z = 0.01 \), 0.1, and 0.3 times solar and for equilibrium and nonequilibrium ionization. For \( 10^{-3} < T < 10^{-2} \text{ K} \) and \( 3 \times 10^{-13} \leq \xi \leq 3 \times 10^{-14} \) photons cm\(^{-2} \) s\(^{-1}\). Scaling to physical values,

\[
\phi(r) \approx 10^{4} n_i^2 r_{100} \left( \frac{\xi}{10^{-14}} \right) \times \left[ 0.8 + 1.3(r f_0)^{1.35} \right] \text{ photons cm}^{-2} \text{ s}^{-1},
\]

(6)

where the central density \( n_i = 10^{3} n_{-3} \) cm\(^{-3}\) and the core radius \( r_i = 100 r_{100} \) kpc. Poor groups show a very broad range of core radii, from tens to hundreds of kpc (Mulchaey et al. 1996), and typical central densities \( n_i \sim 10^{3} \) cm\(^{-3}\) (Pildis & McGaugh 1996).

In Figure 1, we plot \( \phi_i \) as a function of core radius \( r_0 \) for densities \( n_i = (1, 3, 10) \times 10^{-3} \) cm\(^{-3}\), for a metallicity \( Z = 0.1 \) times solar; results differ by \( \approx 20\% \) for the other values of \( Z \). The value of \( \phi_i \) is evaluated at \( r = 350 \) kpc, the assumed distance \( r_{SW} \) of the Galaxy from the center of the LG (solid lines), and at \( r = 0 \) (dashed lines). The fluxes can be very large, exceeding \( 10^9 \) photons cm\(^{-2} \) s\(^{-1}\). However, for \( r_i \ll r_{SW} \), equa-
tion (6) shows that the incident flux at $r_{\text{SW}}$ is greatly diminished compared to the peak value of $\phi_i$.

At distances $r \sim 2r_0$ or less, the ionizing flux produced by a LG corona could be large enough for detection in H$\alpha$: the emission measure is related to the normally incident photon flux by $\xi_0 \approx 1.25 \times 10^{-2} (\phi_i/10^4) \text{ cm}^{-6} \text{ pc}$. However, to produce a significant flux, $n_0$ must be so large that the cooling time $t_c$, within $r \sim r_0$, is short, $t_c \leq 10^9 \text{ yr}$. Even though the LG may be, dynamically, considerably younger than a Hubble time, such a short cooling timescale makes it necessary to consider explicitly the fate of cooling gas.

To estimate the mass cooling flux $M$, we assume that the flow is steady, spherical, and subsonic, and that any gradients in the potential are small compared to the square of the sound speed. In this case the pressure is constant, and mass conservation requires that $M = 4\pi \rho v r^2$; $v$ is the inflow velocity. The cooling radius $r_c$ is set by the condition $r_c \sim t_{\text{cool}}$, the Local Group age. The flow time from $r_c$ is $t_c \sim r_c/v \approx 4\pi \rho r_c^2/M$, where $\rho$ is the gas density at $r_c$. We assume $t_c \sim t_c$, so that the gas has time to cool before reaching $r = 0$. This sets $v \approx r/t_{\text{cool}}$ at $r_c$. If the cooling function $\Lambda$ does not vary rapidly with $T$, the density and temperature within $r_c$ scale nearly as $\rho \propto r/\sqrt{T}$, $T \propto r/r_c$ (Fabian & Nulsen 1977). We have used these scalings to calculate $M$ and $\phi_i$, including the variation of $\xi$ and $\Lambda$ with radius. Figure 2 shows several models. The ionizing flux can be large for small $M$ if $r_c$ is large and $n_0$ is low, but in many cases $M$ is prohibitively large, ruling out any such corona. However, there are several important caveats. Unless the LG is very old, it is unlikely that a steady state flow has been established (e.g., Tabor & Binney 1993), especially as infall of gas into the LG is likely to be ongoing. (If a steady state flow existed with substantial $M$, one would expect the line luminosity—e.g., H$\alpha$—from the cooled gas to be high: see Donahue & Voit 1991.) Furthermore, $M$ is sensitive to the assumed density distribution. For a given metallicity [and therefore $\Lambda(T)$] and LG age, there is a unique value of $n_0$ at which $t_c = t_{\text{cool}}$ and $M \rightarrow 0$. As $n_0$ is raised above this value $M$ increases rapidly, since $r_c$ increases and $M \propto r_c^2$. The value of $\phi_i$ at a given value of $M$ also depends on $Z$, since the reduced $\Lambda$ for low $Z$ means that $n_0$ is larger for a fixed $t_c$. Given these uncertainties, it is not clear that the estimated values of $M$ should be regarded as serious constraints.

4. DISCUSSION

The results of the previous section show that a warm Local Group corona could in principle generate a large enough ionizing photon flux to produce detectable H$\alpha$ emission from neutral hydrogen clouds embedded within it. This would offer an indirect probe of gas which is extremely difficult to observe in emission. Whether the flux seen by clouds at distances comparable to the offset of the Galaxy from the center of the Local Group is high enough for detection depends to a large extent on the core radius characterizing the gas distribution, due to the dropoff in flux for $r$ substantially greater than $r_c$. As shown in Figure 1, for sufficiently large values of $r_0$ and $n_0$, $\phi_i$ can be detectably large even at a few hundred kpc from the LG barycenter.

These large-$n_0$, large-$r_0$ models run into insurmountable difficulties, however, when we examine the additional constraints which can presently be imposed on a LG corona. In Figure 3 we show, shaded in gray, the range in $(r_0, n_0)$ for which the resulting ionizing photon flux is between $\phi_i = 10^4$ and $\phi_i = 10^5$ photons cm$^{-2}$ s$^{-1}$, for radial offsets $r = 0$ (lower region) and $r = r_{\text{SW}} = 350$ kpc (upper region). The cosmic background is probably $\phi_{\text{cos}} \approx 10^4$ photons cm$^{-2}$ s$^{-1}$ (Maloney & Bland-Hawthorn 1999, hereafter MBH). We also plot the following constraints:

1. The assumption that any LG intragroup medium is “typical” (Mulchaey et al. 1996; Pildis & McGaugh 1996) constrains the product $n_0 r_0 \leq 1.5 \times 10^{11}$ cm$^{-2}$, assuming $T_{\text{cool}} \sim 0.2$. This is plotted as the short-dashed line in Figure 3. Any corona which is not unusually rich must lie to the left of this line. This restriction alone rules out any significant contribution to $\phi_i$ at $r_{\text{SW}}$.

2. Assuming that the relative velocity of approach of the...
Galaxy and M31 is due to their mutual gravitational attraction, one can estimate the mass $M_* \text{ of the Local Group (Kahn & Woltjer 1959; q.v., Zaritsky 1994). This “tuning mass” depends somewhat on the choice of cosmology; we take $M_* = 5 \times 10^{12} M_\odot$ within $r = 1$ Mpc of the LG center. The tuning mass constraint is shown as the solid line in Figure 3. As plotted, it is barely more restrictive than the COBE quadrupole constraint (the long-dashed line) and is only more stringent than restriction (1) for large core radii. However, realistically the $M_*$ constraint is much more severe, as the Milky Way and M31 undoubtedly dominate the mass of the Local Group, and so the tuning mass curve in Figure 3 should be moved downward in density by a factor of at least $\sim 5$–10.

3. We possess some information on (more precisely, upper limits to) the actual electron densities at $r \sim r_{\text{MW}}$. Constraints on $n_e(r_{\text{MW}})$ come from two sources. Observations of dispersion measures measure $\mathcal{D}_0$, toward pulsars in the LMC and the globular cluster NGC 5024 (Taylor, Manchester, & Lyne 1993) require a mean $n_e \sim 0.1$; this is a slightly weaker constraint than provided by $M_*$. However, most of this column must be contributed by the Reynolds layer, and some fraction of the $\mathcal{D}_0$ toward the LMC pulsars presumably arises within the LMC, so probably $\leq 10\%$ can be due to a LG corona. Second, a mean density of more than $n_e \sim 0.1$ is allowed by models of the Magellanic Stream; otherwise, the Stream clouds would be plunging nearly radially into the Galaxy (Moore & Davis 1994). This limits the central density to $n_e \sim 0.1 + (r_{\text{MW}}/r_0)^2$. The hatched region in Figure 3 indicates the portion of $(r_0, n_0)$ space in which $n_e(r_{\text{MW}}) \leq 10^{-3} \text{ cm}^{-3}$.

4. As noted earlier (§ 2), WM found evidence for a thermal soft X-ray component at $T_{\text{keV}} \sim 0.2$. If this emission arises in a LG corona, then the corresponding electron density as derived from the emission measure $\varepsilon_{\text{e}}$ is $n_e \sim 3 \times 10^{-4} x^{0.5} \text{ cm}^{-3}$, where $x$ is the extent of emitting region along the line of sight; the density would be $\sim 3$ times smaller for gas of solar rather than zero metallicity. This density constraint is comparable to the $\mathcal{D}_0$ constraint plotted in Figure 3.

Some of these constraints can be avoided if the coronal gas is clumped. The estimates of mass (eq. [4]) and $\phi$ assume a smooth density distribution. However, if the actual densities are a factor $C$ higher than the mean (smoothed) density at a given radius, $\phi$ can be kept constant while reducing both the gas mass and $\mathcal{D}_0$ by $1/C$. This is ad hoc, but if the LG halo is being fueled by ongoing infall, it would not be at all surprising for the gas distribution to be nonuniform. However, the WM X-ray determination is unaffected by clumping, as it is derived from $\varepsilon_{\text{e}}$.

The constraints on a LG corona shown in Figure 3 rule out a significant contribution to the ionizing flux at $r \sim r_{\text{MW}}$. If the core density $n_0$ is high, the core radius $r_0$ must be small; conversely, for large $r_0$, $n_0$ must be low. LG coronae within the allowed region of parameter space can produce fluxes $\phi \gg \phi_{\text{esc}}$, but only on scales of a few tens of kpc, at best. Thus, the maximum volume in which a corona ionizing flux exceeds $\phi_{\text{esc}}$ is only of order 1% of the LG volume, comparable to the volume which can be ionized by galaxies (MBH). This has important implications for the model of Blitz et al. (1998), in which most HVCs are remnants of the formation of the Local Group. If HVCs are at megaparsec distances, $\phi$ will be dominated by the cosmic background. The resulting emission measures will be small: barring unusually favorable geometries, the expected $H\alpha$ surface brightnesses ($\leq 10$ mR) are at the limit of detectability. Any HVCs which are truly extragalactic and detectable in $H\alpha$ would need to lie close to the dominant spiral galaxies (within their “ionization cones”: Bland-Hawthorn & Maloney 1999a, 1999b) or the LG barycenter.

In summary, a warm LG corona which significantly dominates the UV emission within the Local Group is ruled out, although such a corona could contain a cosmologically significant quantity of baryons. More massive galaxy groups could well contain coronae that are both cosmologically important and dominate over the ionizing background. Such coronae could have major impact on the group galaxies through ionization and ram pressure stripping.

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4 We note that, in principle, observations of the O vi doublet at 1032 and 1038 Å are extremely sensitive to the presence of such a corona: for the maximum allowed coronae of Fig. 3, the expected line fluxes could be as large as $F \sim \text{a few } \times 10^{-16} \text{ ergs cm}^{-2} \text{s}^{-1}$. However, the observational difficulties (absorption and scattering of the photons within the ISM of the Galaxy and the very large spatial extent of the source for a LG corona) are severe.