Ionizing Photon Sources within the Local Group

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Abstract. We review the possible sources of ionizing photons within the Local Group. Throughout most of the LG volume, the cosmic background radiation will dominate, but locally (e.g., within \( d \sim 100 \) kpc of the Galactic disk) stellar ionizing photons escaping from galaxies may dominate. The magnitude of the cosmic ionizing background should be determined in the very near future by observations of H\( \alpha \) emission from the outer neutral hydrogen disks of late-type spirals. The detection of the Magellanic Stream in H\( \alpha \) suggests that a few percent of the ionizing photons produced in the Galaxy escape the disk. Neither a warm Local Group corona nor decay photons from a neutrino halo can explain the Stream emission.

1. Introduction

The magnitude and origin of the flux of ionizing photons within the Local Group of galaxies is of considerable interest, for two reasons:

1. Although the total ionizing photon luminosity of the Galaxy is fairly well known, the details of the transfer of this radiation and, in particular, what fraction of the ionizing photons escape to large vertical heights above the midplane - or even escape the disk entirely - has been very uncertain. A significant escaping flux has major implications for many aspects of the interstellar medium.

2. Determination of the level of any cosmic background of ionizing radiation has important cosmological ramifications, since this background (which must exist at some level) arises in a known population of objects, either active galactic nuclei (AGN) or star-forming galaxies, or a combination of the two.

Here we review the possible sources of ionizing photons within the Local Group and the current constraints. After a brief discussion of terminology, we review first the possible cosmological sources, and the present constraints on the magnitude of a cosmic background. We then discuss local (i.e., within the Local Group) sources, for at least one of which (ionizing photons escaping from the...
Milky Way) we now have a direct observational determination. In the final section we discuss the implications of these results, for both the interstellar medium (and, in particular, high-velocity clouds) and cosmology.

2. Terminology

The magnitude of the ionizing background at large redshift is extremely important for the structure of the intergalactic medium, as it sets the level of ionization in the IGM, and there has been a considerable amount of effort to determine the intensity of the ionizing background. The standard quantity which has been generally used in these studies is \( J_\alpha \), the mean intensity (in erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\)) at the Lyman limit. This is rather unfortunate, because for comparison with observations at \( z = 0 \) (where, as discussed below, the limits on the ionizing background come from observations of recombination lines), the most useful quantity is the normally incident ionizing photon flux,

\[
\phi_i \equiv \int_0^1 \mu d\mu \int_{\nu_o}^{\infty} \frac{4\pi J_\nu}{h\nu} d\nu
\]

\[= 4.73 \times 10^{3} \frac{J_{-23}}{\alpha} \text{phot cm}^{-2} \text{s}^{-1} \quad (1)
\]

where \( \mu \) is the cosine of the angle with respect to the normal, \( J_o = 10^{-23} J_{-23} \) erg cm\(^{-2}\) s\(^{-1}\) Hz\(^{-1}\) sr\(^{-1}\) and the spectral index, \( \alpha \), is defined so that the monochromatic flux \( f_\nu \propto \nu^{-\alpha} \). This is simply related to the emission measure,

\[
\mathcal{E}_m \equiv \int n_e n_i dl
\]

(3)

(where \( n_e \) and \( n_i \) are the volume densities of electrons and ions, and \( dl \) is an element of path length along the line of sight) by

\[
\mathcal{E}_m = 2.5 \times 10^{-2} \phi_4 \text{cm}^{-6} \text{pc} \quad (4)
\]

where \( \phi_i = 10^4 \phi_4 \) phot cm\(^{-2}\) s\(^{-1}\) and the numerical coefficient assumes a gas temperature \( T = 10^4 \) K and a face-on slab that is optically thick to the ionizing photons and is being irradiated from both sides. This latter assumption is true for the cosmic background, but will not in general be correct for local sources (e.g., photons escaping from the Galactic disk), where the irradiation is one-sided. The corresponding H\(\alpha \) surface brightness (again for two-sided illumination) is \( I_{\alpha 0} = 9\phi_4 \) mR, where one milliRayleigh is \( 10^3 / \pi \) phot cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\). The H\(\alpha \) flux for a given \( \phi_i \) is essentially independent of both density and temperature, since raising or lowering the recombination rate simply alters the emission measure proportionately, leaving the total column recombination rate unaltered.

3. Sources: Cosmological

Possible cosmological sources fall into two categories: standard (AGN and stellar ionizing photons from galaxies) and exotic (decaying particles). At present
the only possibility which is worth discussing in the latter category is Sciama’s decaying neutrino model; as we will see below, this also counts as a local source of ionizing photons.

### 3.1. Standard

Estimates of the contribution of QSOs to the ionizing background as a function of redshift have a long history (e.g., Sargent et al. 1979; Bechtold et al. 1987; Miralde-Escudé & Ostriker 1990; Haardt & Madau 1996). The most recent values have declined by about a factor of four from the earliest estimates; Haardt & Madau (1996) find \( J_{-23} \sim 1 \) at \( z = 0 \). Shull et al. (1998) have included the contribution from Seyfert galaxies as well as QSOs, and find a slightly larger value: \( J_{-23} \sim 1.6 \). For a canonical spectral index at the relevant photon energies of \( \alpha \approx 1.8 \) (Zheng et al. 1997), this implies a photon flux \( \phi_i = 4200 \text{ phot cm}^{-2} \text{ s}^{-1} \).

It must be noted that these estimates depend not only on the adopted luminosity functions, but also on the magnitude of filtering of the AGN spectrum by the intergalactic medium, which depends on both the spectral shape and the structure which is adopted for the IGM (e.g., Fardal, Giroux, & Shull 1998).

In some ways estimating the ionizing background due to galaxies is more straightforward, since the galaxy luminosity function at low redshift is fairly well understood, and the high ionization of the IGM at the present-day minimizes its influence on the propagation of ionizing photons. (There are, however, still significant uncertainties in the ionizing photon luminosities and the continuum shape for hot stars; see Schaerer & de Koter 1997, and references therein.) Galli et al. (1997) estimate \( J_{-23} \sim 130 f_{\text{esc}} \) at low redshift (\( z \approx 0.5 \)). It is here that the major uncertainty in evaluating the galactic (i.e., stellar) contribution to the ionizing background enters: what fraction \( f_{\text{esc}} \) of the ionizing photons produced by hot stars within a galactic disk escape into the IGM? Theoretical models of the transport of ionizing radiation within the Galactic disk suggest that approximately 10% of the ionizing photons produced within the Milky Way escape the disk entirely (Dove & Shull 1994a). However, observational determinations are clearly necessary.

From observations of four UV-bright starburst galaxies with the Hopkins Ultraviolet Telescope, Leitherer et al. (1995) determined upper limits to \( f_{\text{esc}} \) of 1.7, 4.8, 15, and 1%, (for IRAS 08339+6517, Mrk 1267, Mrk 66, and Mrk 496, respectively) and concluded that the escaping fraction must be small. Their analysis did not take into account the absorption of ionizing radiation by the ISM of the Milky Way, however, and as shown by Hurwitz, Jelinsky & Dixon (1997), this correction raises the upper limits listed above to 5.2, 11, 57, and 3.2%, so that they are no longer significant constraints. (Note also that Hurwitz et al. did not include the effects of absorption by molecular hydrogen, which could raise these upper limits further; see the discussion in §4 of their paper.)

As we will see below, recent observations of Hα emission from the Magellanic Stream suggest that for the Galaxy, \( f_{\text{esc}} \approx 6\% \).

### 3.2. Exotic

In a long series of papers (e.g., Sciama 1990, 1991, 1995a,b), Sciama has argued that a wide range of ionization problems in both the interstellar and intergalactic medium can be understood as the consequence of the decay of a massive neutrino.
species (presumably the $\tau$ neutrino) to a less massive species, accompanied by emission of a photon with energy $E > 13.6$ eV. (Decay occurs if the neutrino weak (i.e., flavor) eigenstates are not also mass eigenstates; see e.g., Boehm & Vogel 1992.) This model predicts a cosmic background due to the decaying neutrinos, with magnitude set by the decay lifetime, $T_\nu$, and by the neutrino mass, $m_\nu$, which determines the photon energy. If one assumes that the mass of the decay product is $\ll$ the mass of the decaying neutrino, then the photon energy produced by the decay is simply $E \simeq m_\nu c^2/2$. The most recent values of the parameters are summarized in Sciama (1998):

\[
\begin{align*}
  m_\nu &\simeq 27.4 \text{ eV} \\
  \tau_\nu &\ = (2 \pm 1) \times 10^{23} \text{s} \\
  \phi_i &\ < 10^5 \text{ photon cm}^{-2} \text{s}^{-1}
\end{align*}
\]

where the upper limit to the cosmic ionizing flux is (by construction) of the order of current upper limits (as measured by H\alpha observations; see below). If the decay photon energy is close to the hydrogen ionization threshold, then the cosmic ionizing background is limited by the redshifting of the photon energy with increasing $z$; this places stringent constraints on the mass of the decaying neutrino. Under the assumption that the mass of the universe is dominated by massive neutrinos (i.e., $\Omega_\nu \simeq 1$, with one flavor of neutrino much more massive than the others), the Hubble constant is also tightly constrained: $H_0 = 55 \pm 0.5$ km s\(^{-1}\) Mpc\(^{-1}\). Recent H\alpha observations of the late-type spiral galaxy NGC 3198 (Bland-Hawthorn 1998; Bland-Hawthorn, Veilleux, & Carignan 1998, in preparation) are, however, in marked disagreement with the predictions of Sciama (1995a): the observed emission is much fainter (by about an order of magnitude) than predicted by the decaying neutrino model (see §4.2 below).

4. The Cosmic Background: Observations

4.1. Indirect

The most straightforward and model-independent way to determine the cosmic ionizing background is simply to measure it directly through observations of recombination lines, such as H\alpha, as discussed in the following section. However, it is only very recently that the sensitivity of these measurements have begin to reach the necessary levels. Other, more indirect methods have therefore been used to estimate the ionizing flux.

The first method is based on the observation that the neutral hydrogen disks in galaxies appear to have rather abrupt truncations, and, more generally, there appears to be very little atomic hydrogen at the boundaries of or outside of galaxies at column densities $N \lesssim 10^{19}$ cm\(^{-2}\) (see summary in van Gorkom 1993). This can be understood as the consequence of ionization of the galactic hydrogen disk by the extragalactic radiation field: in a sort of “inverse Strömgren” problem, the hydrogen disk will be largely ionized once the total column drops below a critical value $N_c$, given by

\[
N_c \approx 1.7 \times 10^{19} \left[ \phi_4 \left( \frac{\sigma_{zz}}{6 \text{ km s}^{-1}} \right) \left( \frac{V_{100}}{\Sigma_{100}} \right) \right]^{1/2} \text{ cm}^{-2}
\]
(Maloney 1993), where $\sigma_{zz}$ is the vertical velocity dispersion of the gas, $V = 100V_{100}$ km s$^{-1}$ is the galactic rotation velocity, and $\Sigma = 100\Sigma_{100}$ $M_\odot$ pc$^{-2}$ is the total surface density (stellar disk + gas + halo; in general, this is dominated by the halo at the relevant radii). Detailed modelling of NGC 3198, as shown in Figure 1, suggests that $\phi_4 \sim 1$. (Note also that while this idea was rediscovered following the famous unpublished NGC 3198 experiment, it actually dates back to Sunyaev 1969 and Bochkarev & Sunyaev 1977; see Maloney 1993 for a summary of the history.) The actual value of $\phi_i$ which best explains the data is somewhat fuzzy, because at gas column densities near the critical value small variations in $N_{\text{tot}}^H$ lead to substantial changes in $N_{\text{HI}}$. This is immediately apparent from Figure 1, in which the neutral column densities for the two halves of the major axis differ rather dramatically beyond $R \sim 25$ kpc, due to modest variations in $N_{\text{HI}}^\text{tot}(R)$. The total hydrogen column as a function of radius has been “reverse-engineered” from the observed $N_{\text{HI}}(R)$ by inverting the neutral hydrogen column (for a choice of $\sigma_{zz}$ and $\phi_i$). A difficult question to address a priori is how much deviation from a smoothly varying $N_{\text{HI}}^\text{tot}(R)$ (especially at or near the HI “edge”) is acceptable in the context of a photoionization explanation for the HI truncations: as the ionizing background intensity is increased, the inferred neutral hydrogen column density becomes smoother. For this reason, the estimates of the necessary value of $\phi_i$ range about a factor of three to either side of $\phi_4 = 1$ (Maloney 1993; Corbelli & Salpeter 1993; Dove & Shull 1994b). This ambiguity can be eliminated by high-sensitivity H$\alpha$ observations, since a corollary of the photoionization modelling is a prediction of the emission measure as a function of radius, as discussed in §4.2.

The other indirect method which has been used to estimate the strength of the cosmic ionizing background is the “proximity effect”. The basic idea is simple: in the vicinity of a luminous source of ionizing photons, such as a quasar, the observed number of Ly$\alpha$ forest lines will decrease, as the (local) ionizing photon flux will reduce the neutral fraction in the absorbers near the source, with the result that for some absorbers the neutral columns will drop below the threshold for detection as a result of the enhanced ionization. It is possible to use this to infer the strength of the cosmic ionizing background ($i.e.$, the sum over all sources of radiation) since the relative importance of the local ionization by a given quasar is inversely proportional to the background intensity. This effect was first noticed by Carswell et al. (1982), and the theoretical analysis was pioneered by Bajtlik, Duncan, & Ostriker (1988). Most subsequent studies have been confined to high redshift ($z \approx 3$). However, Kulkarni & Fall (1993) presented a tentative detection of the proximity effect in a low redshift sample (with $z \lesssim 1$), and derived a mean intensity $J_{-23} \sim 0.6$ at $z \approx 5$. This value is surprisingly low. It must be kept in mind, however, that, due to the small sample size, the error bars on this determination are very large (a point emphasized by Kulkarni & Fall): at the 1$\sigma$ level, the flux could be larger by a factor of six. At the moment this method must be regarded only as suggestive, until much more data are available.

4.2. Direct

Preferable to any indirect determination of the background intensity is, of course, a direct one, and this can in principle be provided by hydrogen recombination
Figure 1. Observed $N_{\text{HI}}$ and derived $N_{\text{H}}^{\text{tot}}$ for the NE (filled circles, solid line) and SW (open circles, dotted line) halves of the major axis of NGC 3198. The total hydrogen column densities are calculated requiring a match to the observed neutral hydrogen columns to within 0.2%.

There is a fairly long history of attempts to measure the cosmic ionizing background using observations of the Hα recombination line (Reynolds et al. 1986; Songaila, Bryant, & Cowie 1989; Kutyrev & Reynolds 1989; Donahue, Aldering & Stocke 1995; Vogel et al. 1995). This has been hampered by the difficulties of observing such faint levels of emission. The current best published
upper limit to the cosmic background is that of Vogel et al. (1995), which is $\phi_4 < 4.5$ at the $3\sigma$ level.

An example of what sort of flux levels are necessary is shown in Figure 2. This is a plot of the predicted emission measure for the same photoionization model of NGC 3198 shown in Figure 1. It is very important to note that the values of $E_m(R)$ plotted in Figure 2 have been corrected for disk inclination $i$ (which was not the case for the corresponding Figure 14 in Maloney 1993), using $i(R)$ from Begeman (1989). Since the inclination $i \gtrsim 71^\circ$ for $R > 16$ kpc, the resulting increase in path length raises the observable emission measures by at least a factor of three above the face-on value for all radii of interest.

Figure 2. Predicted emission measures for the NE (solid line) and SW (dotted line) halves of the major axis of NGC 3198. The values of $E_m(R)$ are those predicted by the photoionization model shown in Figure 1, and have been corrected for inclination.

The data on NGC 3198 presented by Bland-Hawthorn (1998) (also Bland-Hawthorn, Veilleux, & Carignan 1998, in preparation), showing H$\alpha$ emission at the level of $0.1 \text{cm}^{-6} \text{pc}$, strongly suggest to the first author that the cosmic background has been detected, at a level $\phi_4 \sim 1$. The second author is less convinced, and believes the detected emission may be due to internal sources. There should be two ways of discriminating between these possibilities:

- If the emission is really due to the cosmic background, then the outskirts of other spiral galaxies will show emission at identical (inclination-corrected) levels. For example, the outer HI disk of M31, which is at an inclination of about $77^\circ$, should exhibit the same H$\alpha$ surface brightness as NGC 3198.
• The radial distribution of emission measure will be crucial. As is apparent in Figure 2, $E_m(R)$ is predicted to be quite flat in the case of a uniform cosmic background. This is simply the result of the fact that nearly all of the incident ionizing photons are absorbed by the gas disk (see e.g., Vogel et al. 1995); thus, until the HI edge is reached, there is merely a slow radial fall-off as the absorbed fraction declines slightly with the decrease in the total column density. Beyond the HI edge the emission measure decreases rapidly, since most of the gas is now ionized rather than neutral. In contrast, if the observed emission measure is due to internal sources (such as self-irradiation of a warped disk), in general $E_m$ will be a strong function of radius, depending on how the irradiation varies with $R$. Note that $E_m$ may either decrease or increase with $R$ in this case; a fuller discussion of the behavior expected in different scenarios will be presented in Maloney, Bland-Hawthorn & Freeman (1998).

Further observations are clearly required to settle this issue; fortunately, the necessary instrumental sensitivity and data reduction techniques are in hand, and rapid progress in this area is to be expected.

5. Sources: Local

As for the cosmological background, sources here come in two flavors: standard, and exotic. Under “standard” are ionizing photons produced by hot stars within Local Group galaxies which escape from the galactic disks; as we discuss below we now have a good estimate of the escape fraction for the Milky Way. In addition, there is the possibility that the ionizing photon flux from a Local Group “corona” of warm gas might be significant (Maloney & Bland-Hawthorn 1998). Finally, Sciama’s decaying neutrino model also enters as a local source, because the neutrinos which make up the dark matter haloes of the Local Group galaxies (in this model) will make a local contribution to the ionizing photon flux, in addition to the cosmological contribution from neutrino decay.

5.1. Stellar $\phi_i$ from Local Group Galaxies

The ionizing photon luminosity of the Milky Way is fairly well-determined; various estimates agree on $N_i \approx 3 \times 10^{53}$ phot s$^{-1}$ (see Bland-Hawthorn & Maloney 1998), with an uncertainty of about 30%. As noted earlier, the question as to what fraction of these photons escape from the disk to the halo and beyond has remained unsettled. However, a recent observation has settled this question. Weiner & Williams (1996) detected H$\alpha$ emission from the Magellanic Stream, with emission measures $E_m \approx 0.5 - 1$ cm$^{-6}$ pc. From equation (4) (but corrected to one-sided irradiation), this implies normally incident ionizing photon fluxes $\phi_i \approx 4 - 8 \times 10^5$ phot cm$^{-2}$ s$^{-1}$. Although Weiner & Williams argued for a shock origin, it is difficult to make these models work, and it is far more likely that the H$\alpha$ emission is produced by ionizing photons produced in the disk of the Milky Way which have escaped the disk to impinge upon the Stream. The geometry is extremely favorable, as the Stream passes more or less directly over the Galactic disk. As discussed in detail in Bland-Hawthorn & Maloney (1997, 1998) and Bland-Hawthorn (this volume), it is possible to use the Stream detections to
determine what fraction of the ionizing photons produced within the Galactic disk escape; this fraction \( f_{\text{esc}} \approx 6\% \). This percentage is in reasonable agreement with the ionizing photon flux needed to explain the diffuse ionized gas within the Galactic disk (the Reynolds layer), and with models of photon transport and escape within the Galaxy (Reynolds 1990; Miller & Cox 1993; Dove & Shull 1994a).

With the normalization provided by the Magellanic Stream detections, it is possible to calculate the shape and intensity of the ionizing radiation field produced by the Milky Way, and, in particular, to calculate the expected emission measures for clouds near to the Galactic disk. Ionizing photons escaping from the Galaxy will dominate over the cosmic ionizing background out to a radius

\[
 r_{MW} \sim 120 \left( \frac{f_{\text{esc}}}{0.05} \phi_{i,\text{cos}} \right)^{1/2} \text{kpc}. \tag{6}
\]

The predicted emission measures can be used to determine distances for the high-velocity clouds (Bland-Hawthorn et al. 1998). This method is probably only reliable for heights \( Z \gtrsim 10 \text{ kpc} \) or so from the disk midplane, so that structure in both the distribution of ionizing photons and obscuring material within the disk is averaged out. However, we note that the model presented in Bland-Hawthorn and Maloney (1997, 1998) and Bland-Hawthorn et al. (1998) predicts the distances to the M and A HVC complexes, detected in H\( \alpha \) by Tufte, Reynolds & Haffner (1998), to within a factor of two. Future H\( \alpha \) observations at current levels of sensitivity will revolutionize the study of HVCs.

### 5.2. A Local Group Corona

Is there a significant mass of gas associated with the Local Group? Only a small fraction of the mass of baryons predicted by standard Big Bang nucleosynthesis (e.g., Olive, Steigman, & Walker 1991) is actually observed at \( z = 0 \) (e.g., Persic & Salucci 1992). A recent inventory of the observed baryons is given in Fukugita, Hogan, & Peebles (1998). If we parameterize the distribution of gas in a group (assumed spherical) by the density distribution

\[
 n(r) = \frac{n_o}{1 + (r/r_o)^2} \tag{7}
\]

where \( n_o \) and \( r_o \) are the core density and core radius, respectively, then X-ray studies of poor groups of galaxies (which are usually still substantially richer than the Local Group) typically find the product

\[
 n_o r_o T_{\text{keV}} \sim 3 \times 10^{20} \text{ cm}^{-2} \tag{8}
\]

where \( T_{\text{keV}} \) is the gas temperature expressed in keV. However, there is a systematic dependence of the detection fraction on the morphology of the group galaxies: groups dominated by ellipticals are generally described by equation (8), with \( T_{\text{keV}} \sim 1 \), while spiral-rich groups generally do not show evidence for a diffuse intragroup medium; only individual galaxies are detected (Pildis & McGaugh 1996; Mulchaey et al. 1996). The simplest interpretation is, of course,
that spiral-dominated groups do not have such an intragroup medium. However, Mulchaey et al. (1996) suggested that the non-detections might be due not to an absence of gas, but to lower gas temperatures in the spiral-rich groups: the velocity dispersions of spiral-rich groups are significantly lower than those of elliptical-rich groups, and imply gas temperatures $T_{\text{keV}} \approx 0.2 - 0.3$. Gas at such temperatures is extremely difficult to observe directly, even at soft X-ray wavelengths. In fact, from deep ROSAT images, Wang & McCray (1993) found evidence for a diffuse thermal component with $T_{\text{keV}} \sim 0.2$ and electron density, $n_e \sim 1 \times 10^{-2} \, x_{\text{kpc}}^{-0.5} \, \text{cm}^{-3}$ (assuming primordial gas) where $x_{\text{kpc}}$ is the line-of-sight depth within the emitting gas in kiloparsecs. With no information at present available on the spatial extent of the emission, it is impossible to say whether this is very local gas (within the disk of the Galaxy, or a Galactic corona), or more extended emission associated with the potential of the Local Group itself. In the continuing infall scenario advocated by Blitz et al. (1998) for the origin of the HVCs, a substantial fraction of the infalling clouds will collide (preferentially near the barycenter of the Local Group, approximately midway between M31 and the Milky Way) and shock up to the virial temperature, $T_{\text{vir}} \sim 0.2 \, \text{keV}$, leading eventually to the formation of a group corona.

In Maloney & Bland-Hawthorn (1998), we considered whether such a Local Group corona could be detected indirectly, through the ionizing photon flux produced as the gas cools. This can in principle be important, for example in clusters of galaxies, where the resulting flux can exceed the cosmic background by an order of magnitude. However, in the Local Group, the other constraints which can be imposed on such a corona – in particular, dispersion measure observations toward pulsars in the LMC and distant globular clusters, the “timing mass”, and the X-ray observations mentioned above – rule out an ionizing flux from a corona which is significant (i.e., exceeds the probable cosmic background by a substantial factor) for scales larger than a few tens of kpc. Basically, if the core radius is large (so that the flux from the corona is important on the scale of the Local Group), then the core density must be low to avoid violating these other constraints. Such a corona could still contain a substantial amount of mass: the direct observational limits on warm gas in the Local Group are still not very stringent.

### 5.3. Decay Photons from the Galactic Halo

The immense number (of order $10^{76}$) of neutrinos in the halo of the Milky Way in Sciama’s model will produce a local ionizing photon flux, as they slowly decay on a timescale $T_{\nu} \sim 10^{23}$ seconds. Assuming a nonsingular isothermal sphere for the neutrino density distribution (as in equation [7]), the flux from a neutrino halo can be written

$$
\phi_i \sim 2 \times 10^6 \left( \frac{T_{\nu}}{10^{23}} \right)^{-1} \frac{V_{100}^2}{(r_o^2 + r^2)^{1/2}} \, \text{phot cm}^{-2} \, \text{s}^{-1}
$$

where $V_{100}$ is the (asymptotic) velocity of the halo scaled to 100 km s$^{-1}$, and we have assumed that the galactic disk is completely opaque to the decay photons, so that only one-half of the halo contributes to the flux on either side of the disk. For the parameters of Sciama (1998) and halo parameters appropriate to the Milky Way, the predicted flux is $\phi_i \approx 2 - 3 \times 10^5$ phot cm$^{-2}$ s$^{-1}$ at $r \approx 10$ kpc.
(assuming a core radius of several kpc and a rotation velocity of 200 km s$^{-1}$). This is in the range of the ionizing photon fluxes found by Tuft et al. (1998) for HVC complexes A and C. However, neither the Milky Way nor the LMC can produce the fluxes necessary for the Stream detections through decay of halo neutrinos.

6. Summary

Throughout most of the Local Group volume, the ionization will be dominated by the cosmic background, at a level $\phi \sim 10^4$ phot cm$^{-2}$ s$^{-1}$ which is still somewhat uncertain but which will be pinned down by H$\alpha$ observations in the very near future. The cosmic background itself is probably dominated by stellar photons escaping from galaxies, if the escape fraction of photons from the Milky Way (as determined from the detection of the Magellanic Stream in H$\alpha$) is typical of $L_*$ galaxies. Within $r \sim 100$ kpc of the Milky Way (depending on the angle with respect to the axis of the Galaxy: see Bland-Hawthorn, this volume), the flux of ionizing photons escaping the disk will exceed the background, but this is only of order 1% of the Local Group volume; a warm Local Group corona can only influence a similarly small fraction of the LG volume. This has very important implications for the suggestion of Blitz et al. (1998) that the HVCs are relics of the formation of the Local Group (see also Blitz, this volume): if most HVCs are actually at distances of order 1 Mpc, then they will be very faint in H$\alpha$ emission, as they will be illuminated only by the cosmic background. This provides a direct observational test of the model.

Acknowledgments. PRM acknowledges support from the Astrophysical Theory Program through NASA grant NAG5-4061, and would like to thank JBH & Sue for their splendid hospitality. The authors sincerely hope that Dennis will forgive us our conclusions regarding the decaying neutrino model! Our deep admiration for him remains undiminished.

References

Bajtlik, S., Duncan, R.C., & Ostriker, J.P. 1988, ApJ, 327, 570
Bechtold, J., Weymann, R.J., Lin, Z., & Malkan, M.A. 1987, ApJ, 315, 180
Begeman, K.G. 1989, A&A, 223, 47
Bland-Hawthorn, J. 1998, in The Third Stromlo Symposium: The Galactic Halo, ed. B.K. Gibson, T. Axelrod, & M.E. Putnam (San Francisco: Astronomical Society of the Pacific), in press.
Bland-Hawthorn, J., & Maloney, P.R. 1998, ApJ (Letters), in press.
Bland-Hawthorn, J., Veilleux, S., Cecil, G.N., Putman, M.E., Gibson, B.K., & Maloney, P.R. 1998, MNRAS, 299, 611
Blitz, L., Spergel, D.N., Teuben, P.J., Hartmann, D., & Burton, W.B. 1998, ApJ, in press.
Bochkarev, N.G., & Sunyaev, R.A. 1977, AZh, 54, 957 (translated in Soviet Astr., 21, 542)
Boehm, F., & Vogel, P. 1992, Physics of Massive Neutrinos (Cambridge: Cambridge University Press)
Carswell, R.F., Whelan, J.A.J., Smith, M.G., Boksenberg, A., & Tytler, D. 1982, MNRAS, 198, 91
Corbelli, E., & Salpeter, E.E. 1993, ApJ, 419, 104
Donahue, M., Aldering, G., & Stocke, J.T. 1995, ApJ, 450, L45
Dove, J.B., & Shull, J.M. 1994a, ApJ, 423, 196
Dove, J.B., & Shull, J.M. 1994b, ApJ, 430, 222
Fardal, M.A., Giroux, M.L., & Shull, J.M. 1998, AJ, 115, 2206
Fukugita, M., Hogan, C.J., & Peebles, P.J.E. 1998, ApJ, 503, 518
Giallongo, E., Fontana, A., & Madau, P. 1997, MNRAS, 289, 629
Haardt, F., & Madau, P. 1996, ApJ, 461, 20
Hurwitz, M., Jelinsky, P., & Dixon, W.V.D. 1997, ApJ, 481, L31
Kulkarni, V.P., & Fall, S.M. 1993, ApJ, 413, L63
Kutyrev, A.S., & Reynolds, R.J. 1989, ApJ, 344, L9
Leitherer, C., Ferguson, H.C., Heckman, T.M., & Lowenthal, J.D. 1995, ApJ, 454, L19
Maloney, P. 1993, ApJ, 414, 41
Maloney, P.R., & Bland-Hawthorn, J. 1998, ApJ, submitted.
Maloney, P.R., Bland-Hawthorn, J., & Freeman, K.C. 1998, in preparation.
Müller, W.W., & Cox, D.P. 1993, ApJ, 417, 579
Miralde-Escudé, J., & Ostriker, J.P. 1990, ApJ, 350, 1
Mulchaey, J.S., Davis, D.S., Mushotzky, R.F., & Burstein, D. 1996, ApJ, 456, 80
Olive, K.A.; Steigman, G., & Walker, T.P. 1991, ApJ, 380, L1
Persic, M., Salucci, P. 1992, MNRAS, 258, 14P
Pildis, R.A., & McGaugh, S.S. 1996, ApJ, 470, L77
Reynolds, R.J. 1990, in Galactic & Extragalactic Background Radiation, ed. S. Bowyer & C. Leinert, (Dordrecht: Kluwer), 157
Reynolds, R.J., Magee, K., Roesler, F.L., Scherb, F., & Harlander, J. 1986, ApJ, 309, L9
Sargent, W.L.W., Young, P.J., Boksenberg, A., Carswell, R.F., & Whelan, J.A.J. 1979, ApJ, 230, 49
Schaerer, D., & de Koter, A. 1997, A&A, 322, 598
Sciama, D. 1998, A&A, 335, 12
Sciama, D. 1995a, MNRAS, 276, L1
Sciama, D. 1995b, ApJ, 448, 667
Sciama, D. 1991, ApJ, 367, L39
Sciama, D. 1990, ApJ, 364, 549
Shull, J.M., Roberts, D., Giroux, M.L., Penton, S.V., & Fardal, M.A. 1998, AJ, submitted.
Songaila, A., Bryant, W., & Cowie, L.L. 1989, ApJ, 345, L71
Sunyaev, R.A. 1969, ApL, 3, 33
Tufte, S.L., Reynolds, R.J., & Haffner, L.M. 1998, ApJ, 504, 773
van Gorkom, J.H. 1993, in The Environment and Evolution of Galaxies, ed. J.M. Shull & H.A. Thronson (Dordrecht: Reidel), p. 435.
Vogel, S.N., Weymann, R., Rauch, M., & Hamilton, T. 1995, ApJ, 441, 162
Wang, Q.D., & McCray, R.M. 1993, ApJ, 409, L37
Weiner, B.J. & Williams, T.B. 1996, AJ, 111, 1156
Zheng, W., Kriss, G.A., Telfer, R.C., Grimes, J.P., & Davidsen, A.F. 1997, ApJ, 475, 469