The Galactic Halo Ionizing Field

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Abstract

There has been much debate in recent decades as to what fraction of ionizing photons from star forming regions in the Galactic disk escape into the halo. The recent detection of the Magellanic Stream in optical line emission at the CTIO 4m and the AAT 3.9m telescopes may now provide the strongest evidence that at least some of the radiation escapes the disk completely. We present a simple model to demonstrate that, while the distance to the Magellanic Stream is uncertain, the observed emission measures ($\mathcal{E}_m \approx 0.5 - 1$ cm^{-6} pc) are most plausibly explained by photoionization due to hot, young stars. This model requires that the mean Lyman-limit opacity perpendicular to the disk is $\tau_{LL} \approx 3$, and the covering fraction of the resolved clouds is close to unity. Alternative sources (e.g. shock, halo, LMC or metagalactic radiation) contribute negligible ionizing flux.

Keywords: interstellar medium – intergalactic medium – individual object: Magellanic Stream – Galaxy: corona, halo – interferometry

1 Introduction

There has been extensive theoretical and observational interest in establishing what fraction of the total ionizing luminosity from the stellar disk of the Milky Way and other galaxies escapes into the halo and the intergalactic medium (*e.g.,* Miller & Cox 1993; Dove & Shull 1994; Leitherer & Heckman 1995). Diffuse ionized gas between HII regions in half a dozen well studied galaxies suggests that a significant fraction escapes to ionize the ambient ISM (e.g. Hoopes, Walterbos & Greenawalt 1996; Ferguson *et al.*1996). Broadly speaking, if the optical depth at the Lyman limit is τ_{LL}, these observations require $\tau_{LL} \approx 1$ on the scale of the diffuse disk gas. The vertically extended Reynolds Layer requires that $\tau_{LL} \approx 2$ to explain the observed line emission (Reynolds 1990). We now show that the observed Hα emission measures at the distance of the Magellanic stream (0.5–1 cm^{-6} pc in the MS II–IV clumps) are consistent with ionization by the Galactic disk (Weiner & Williams 1996; q.v. Bland-Hawthorn 1997), providing $\tau_{LL} \approx 3$ perpendicular to the disk. More detailed calculations are given in Bland-Hawthorn & Maloney (1996).

2 Galactic photoionization model

The emission measure $\mathcal{E}_m$ from the surface of a cloud embedded in a bath of ionizing radiation gives a direct gauge, independent of distance, of the ambient radiation field beyond the Lyman continuum (Lyc) edge (*e.g.,* Hogan & Weymann 1979). This assumes that the covering fraction (κ) *seen by the ionizing photons* is known and that there are sufficient gas atoms to soak up the incident ionizing photons. We assume an electron temperature $\mathrm{T}_e \simeq 10^4$K, as expected for gas photoionized by stellar sources, for which the Case B hydrogen recombination coefficient is $\alpha_B \simeq 2.6 \times 10^{-13}(10^4/T_e)^{0.75}$ cm^3 s^{-1}. At these temperatures, collisional ionization processes are negligible. In this case, the column recombination rate in equilibrium must equal the normally incident ionizing photon flux, $\alpha_B n_e N_{H^+} = \varphi_i$, where φ_i is the rate at which Lyc photons arrive at the cloud surface (photons cm^{-2} s^{-1}), n_e is the electron density and N_{H^+} is the column density of ionized hydrogen. The emission measure is just $\mathcal{E}_m = \int n_e n_{H^+}\, dl = n_e n_{H^+} L$ cm^{-6} pc where L is the thickness of the ionized region. The resulting emission measure for an ionizing flux φ_i is then $\mathcal{E}_m = 1.25 \times 10^{-2} \varphi_4$ cm^{-6} pc where $\varphi_i = 10^4 \varphi_4$. For an optically thin cloud in an isotropic radiation field, the solid angle from which radiation is received is $\Omega = 4\pi$, while for one-sided illumination, $\Omega = 2\pi$. For the models we will be considering, however, J_ν is anisotropic and Ω can be considerably less than 2π.

In order to estimate φ_i, we develop an idealized model for predicting the Hα emission measure at the distance of the Magellanic Stream. The ionizing stars are assumed to be isotropic emitters confined to a thin disk in the $x - y$ plane (or the $X - Y$ plane in Galactic Coordinates, e.g. Fig. 1). For a cloud C at position $(x_0, 0, z_0)$ a distance R from an arbitrary patch of the disk dA, the received flux f_d (in units of erg cm^{-2} s^{-1} Hz^{-1}) from ionizing disk sources with specific intensity ζ_ν through a solid angle $d\Omega$ is

$$f_d = \int \zeta_\nu \; \mathrm{d}\Omega = \int \zeta_\nu \; \cos\theta \; dA(r,\phi)/R^2 \tag{1}$$

where $dA = r\ dr\ d\phi$ and

$$R = x_0^2 + z_0^2 + r^2 - 2x_0 r \cos\phi. \tag{2}$$

The angle θ is the polar angle measured from the positive z axis through dA to the line extending from dA to C. Thus, at an arbitrary point in the galaxy halo, the ionizing photon flux from the disk (in units of photons cm^{-2} s^{-1}) is

$$\varphi_d(r,\phi) = \int n_d(r,\phi) \; \cos\theta \; dA(r,\phi)/R^2 = \int d\sigma(r,\phi)\cos\theta \; /R^2 \tag{3}$$

for which n_d and dσ are the surface photon density and brightness, respectively, within each disk element dA.

For the opaque disk model, the patch dA is observed through the intervening disk interstellar medium (ISM) such that $d\sigma' = e^{-\tau_{LL}(r,\phi)}\ d\sigma$. For a disk population of OB stars, we consider an axisymmetric exponential disk with scale length r_d, $n_d(r) = n_0 e^{-r/r_d}$. We adopt a radial scale length of $r_d = 3.5$ kpc (Kent, Dame & Fazio 1991) and all integrations are performed out to 25 kpc in radius since there is some evidence for faint HII regions at these large radii (de Geus *et al.* 1993). Vacca *et al.* (1996) have compiled a list of 429 O stars within 2.5 kpc of the Sun from which they determine an ionizing surface density of $n(r_\odot) = 3.74 \times 10^7$ phot cm^{-2} s^{-1} where $r_\odot$ is the radius of the Solar Circle. After an exhaustive study of the literature, Reid (1993) finds $r_\odot = 8.0 \pm 0.5$ kpc. Thus, from equation (1), we derive $n_0 = 3.7 \times 10^8$ phot cm^{-2} s^{-1}.

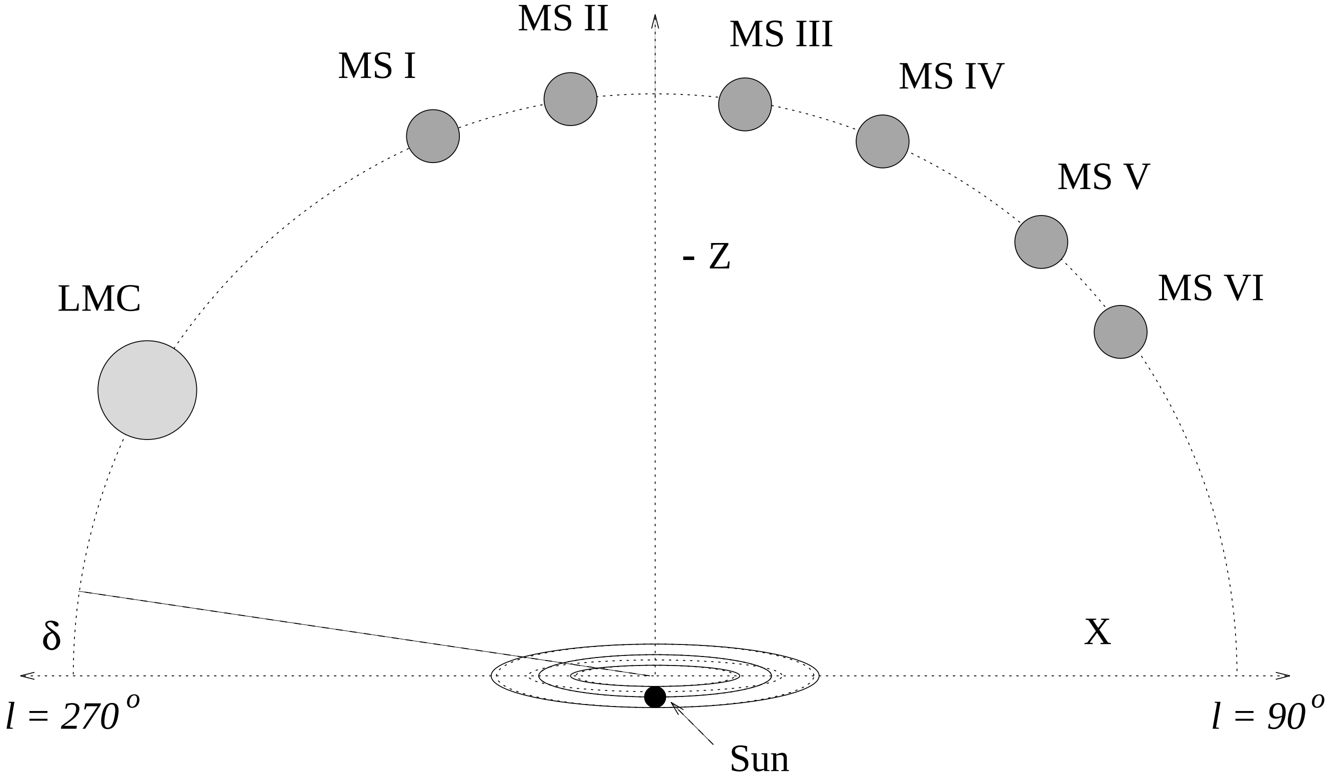

Figure 1: An illustration of the LMC and the dominant clouds in the Magellanic Stream (Mathewson & Ford 1984). The LMC and the Stream have been projected onto the Galactic X-Z plane. We have ignored small projection errors resulting from our vantage point at the Solar Circle. The angle δ is measured from the negative X axis towards the negative Z axis where $\delta = -b$ ($0° \leq \delta \leq 90°$) and $\delta = b + 180°$ ($90° \leq \delta \leq 180°$). In reality, the orbit of the Stream lies closer to the Great Circle whose longitude is $l = 285°$.

3 Photoionization of the Magellanic Stream

The Stream lies along a great arc which extends for more than 100° (*e.g.,* Mathewson, Cleary & Murray 1974). Fig. 1 illustrates the relationship of the LMC to the Magellanic Stream above the Galactic disk (Mathewson & Ford 1984). We shall make the assumption that the Stream lies along a circular orbit, close to the X-Z plane, originating from the Lagrangian point between the LMC and SMC. The Cepheid distance moduli indicate that for the LMC $(m-M)_0 = 18.47 \pm 0.15$, which implies a distance of 49.4±3.4 kpc (Feast & Walker 1987); for the SMC, $(m-M)_0 = 18.83 \pm 0.15$ which implies 58.3±4.0 kpc (Feast 1988). Thus, we shall assume an average galactocentric radius of 55 kpc for the Stream. This is an oversimplification since most computed orbits for the LMC-SMC system imply substantial ellipticity with the Galaxy at a focal point (*e.g.,* Lin, Jones & Klemola 1995). Our model is consistent with the distance measured by Gardiner *et al.* (1994) towards MS VI, but not with the much smaller value of 20 kpc determined by Moore & Davis (1994).

In Fig. 2, we present a meridional plot of the halo radiation field for $\tau_{LL} = 2$. While the distance to the Magellanic Stream is uncertain, the expected Hα emission measure for the opaque disk model should be easily detectable. For distances of (20,40,60) kpc, φ_4 takes values of (710,215,105) $\times 10^4$ phot cm^{-2} s^{-1} (Fig. 3). From equation (7), the expected $\mathcal{E}_m$ values are (9.0,2.7,1.3) cm^{-6} pc, or equivalently, (18,5.4,2.6) $\times 10^{-18}$ erg cm^{-2} s^{-1} arcsec^{-2}. The Weiner & Williams (1996) detections along the stream are 370, 210 and 200 milliRayleighs[1] or, equivalently, $\mathcal{E}_m$ values of (1.1,0.63,0.60) cm^{-6} pc. The Hα measurements of Weiner & Williams (1996) are within range of the model values, particularly since the Stream distance is at the far end of our range.

In Fig. 3, we present the predicted emission measure along the Stream after projecting the clouds into the X-Z plane, where the observer is assumed to be at the Galactic Centre. If we assume κ is close to unity and remains constant along the Stream, several conclusions follow immediately. *The Galactic disk is unlikely to be transparent to ionizing photons otherwise the Magellanic Stream would be mostly ionized.* The shape of the $\mathcal{E}_m$ curve gives an independent assessment of the disk opacity, but this is sensitive to departures from a circular trajectory. With relatively few unknowns, the mean UV opacity of the Galactic disk can be determined after a comprehensive observational campaign along the Stream. If the Stream orbit is highly flattened (Moore & Davis 1994), the solid line in Fig. 3 becomes significantly more boxy at large δ, and possibly even sharply rising towards the edges before turning over. The expected value of $\mathcal{E}_m$ at MS VI ($\delta = 135°$) could be almost an order of magnitude higher for a distance of 20 kpc compared with our adopted value. The major limitation of our model is the poorly known cloud geometry and HI covering fraction.

In the interests of brevity, we do not discuss alternative ionizing sources (e.g. shock or halo sources) as these are expected to be entirely negligible. For illustrative purposes only, we include the expected ionization from the LMC and halo bremsstrahlung in Fig. 3. For the coronal gas, we assume an isothermal sphere with central density 2×10^{-3} cm^{-3}, scale length 10 kpc and electron temperature 2×10^6K (0.2 keV). The LMC is treated as a point source radiating 5×10^{51} ionizing photons per second. For a complete discussion, we refer readers to Bland-Hawthorn & Maloney (1996).

The influence of the corona is only likely to be observable at extreme δ angles where emission from the upper cloud face is expected to dominate. At δ angles larger than 150°, the isothermal halo acts much like a distant point source so would be difficult to distinguish from the LMC ionization. The LMC radiation field is not expected to substantially ionize the Magellanic Stream (MS I−VI) although, presumably, it has a major impact on the outer parts of the Milky Way

[1] 1 Rayleigh is $10^6/\pi$ phot cm^{-2} s^{-1} sr^{-1} or 2.41×10^{-10} erg cm^{-2} s^{-1} sr^{-1} at Hα.

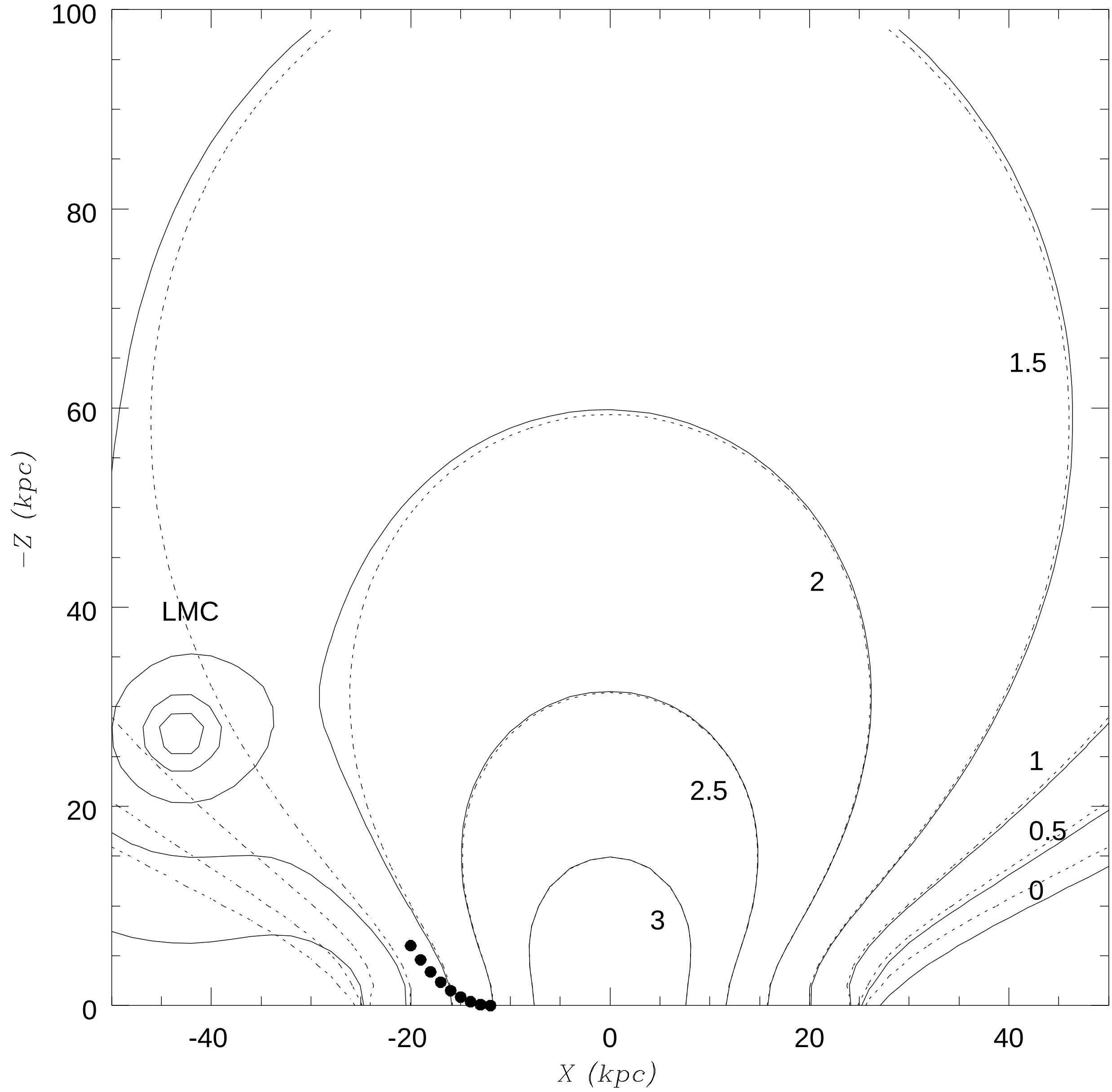

Figure 2: Meridional plot showing the probable contribution of the LMC to the opaque-disk halo radiation field (solid lines). The dotted lines are for the opaque-disk model in Fig. 3. The position of the LMC in Galactic coordinates lies within 2 kpc of the plane $Y = 0$ (Fujimoto & Sofue 1976). The figure shows a 100 kpc $\times$ 100 kpc intersection of the non-axisymmetric radiation field in the plane $Y = 0$. The dots represent the HI warp in the outer parts of the Galaxy close to the line of longitude $l = 270°$ (Burton 1988).

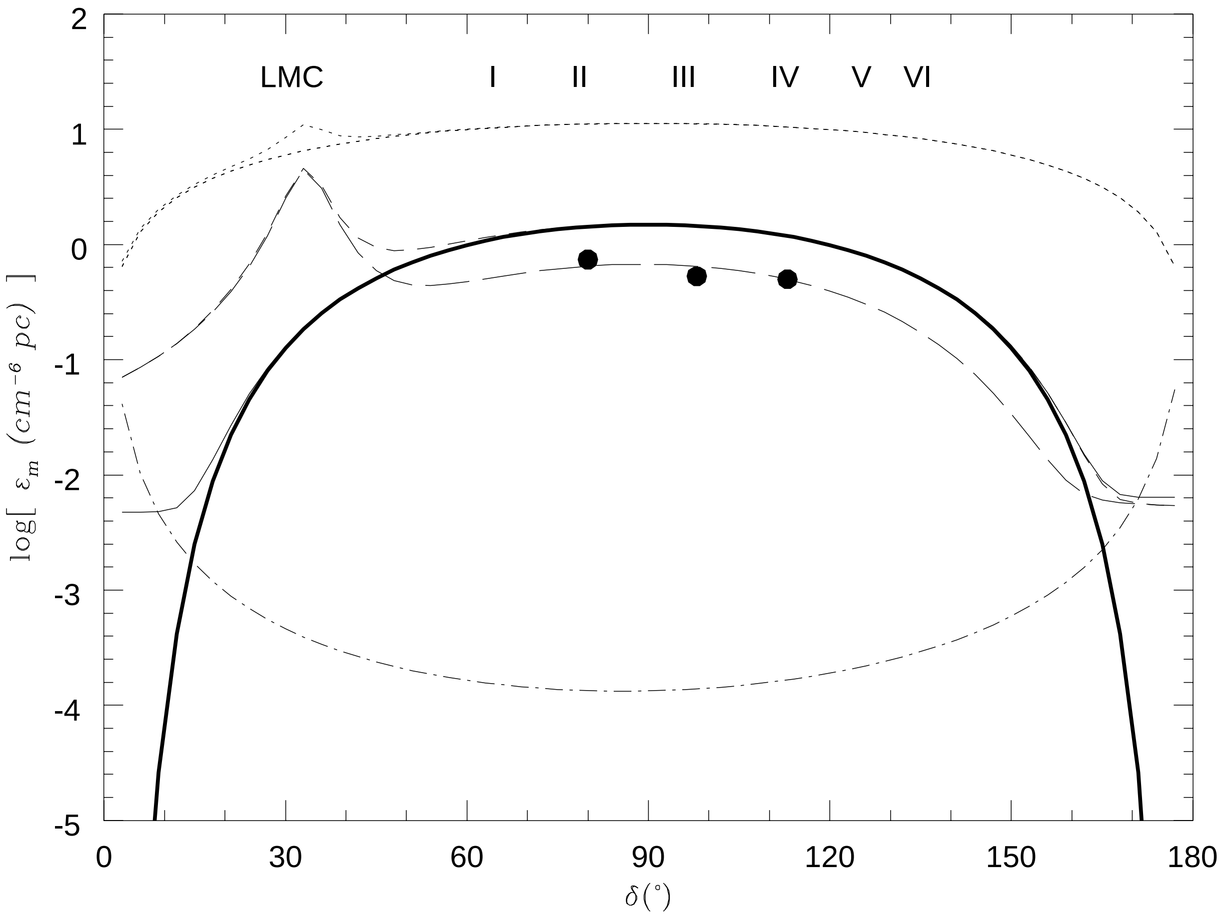

Figure 3: The predicted Hα emission measure along the Magellanic Stream as a function of δ. The vertical axis has units of log(cm^{-6} pc); these can be converted to log(Rayleighs) by subtracting 0.48. The dotted curves (top) assume an optically thin Galactic disk with and without the LMC ionizing field. The solid lines assume an opaque ionizing disk with (thin line) and without (thick line) a bremsstrahlung halo. The LMC contribution to the opaque disk(+halo) model is shown by the short-dash ($\tau_{LL} = 2$) and long-dash ($\tau_{LL} = 2.8$) curves. The dot-dash curve is $\mathcal{E}_m$(Hα) predicted from the upper side of the Magellanic Stream due to the bremsstrahlung halo. The solid points are the $\mathcal{E}_m$ measurements of Weiner & Williams (1996).

in the direction l = 270° (see Figs. 2 and 3). If there are no UV-bright companions, the outer extremities of opaque disks fall inside a 'toroidal shadow' which sees only a very weak ionizing field from the Galactic halo. If the outer warp in the HI disk is not severe ($\leq 10°$ from center to edge), the ionization of cold gas at large radius should be dominated by the cosmic UV background. The current 2σ upper limit on the flux, φ_4= 3.8 (q.v. Bland-Hawthorn 1997), indicates that the cosmic background is expected to produce an equivalent emission measure less than $\mathcal{E}_m = 0.05$ cm^{-6} pc.

In summary, for a mean Stream distance of 55 kpc, if $\kappa = 1$, the Hα detections indicate $\tau_{LL} \approx 3$ perpendicular to the Galactic disk such that only 5% of the ionizing radiation from the disk escapes into the halo. Notably, Domgorgen & Mathis (1994) have obtained the same result using an entirely different approach. While OB stars should dominate the ionization balance, just how the ionizing radiation escapes from the star-forming regions into the halo is still somewhat unclear, although recent theoretical models have begun to address this issue (Miller & Cox 1993; Dove & Shull 1994).

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