Publ. Astron. Soc. Aust., 1997, 14, 59–63

The Galactic Halo Ionising Field

J. Bland-Hawthorn[1] and P. R. Maloney[2]

[1]Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia
jbh@aaossz.aao.gov.au
[2]CASA, University of Colorado, Boulder, CO 80309-0389, USA

Received 1996 October 14, accepted 1996 December 17

Abstract: There has been much debate in recent decades as to what fraction of ionising 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 4 m and the AAT 3·9 m 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 ($\varepsilon_m \approx 0{\cdot}5 - 1$ cm^{-6} pc) are most plausibly explained by photoionisation due to hot, young stars. This model requires that the mean Lyman-limit opacity perpendicular to the disk is $\tau_{\rm LL} \approx 3$, and the covering fraction of the resolved clouds is close to unity. Alternative sources (e.g. shock, halo, LMC or metagalactic radiation) contribute negligible ionising 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 ionising 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 ionised gas between H II regions in half a dozen well studied galaxies suggests that a significant fraction escapes to ionise the ambient ISM (e.g. Hoopes, Walterbos & Greenawalt 1996; Ferguson et al. 1996). Broadly speaking, if the optical depth at the Lyman limit is $\tau_{\rm LL}$, these observations require $\tau_{\rm LL} \approx 1$ on the scale of the diffuse disk gas. The vertically extended Reynolds Layer requires that $\tau_{\rm LL} \approx 2$ to explain the observed line emission (Reynolds 1990). We now show that the observed Hα emission measures at the distance of the Magellanic stream ($0{\cdot}5$–1 cm^{-6} pc in the MS II–IV clumps) are consistent with ionisation by the Galactic disk (Weiner & Williams 1996; cf. Bland-Hawthorn 1997, present issue p. 64), providing $\tau_{\rm LL} \approx 3$ perpendicular to the disk. More detailed calculations are given in Bland-Hawthorn & Maloney (1996).

2 Galactic Photoionisation Model

The emission measure ε_m from the surface of a cloud embedded in a bath of ionising 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 ionising photons* is known and that there are sufficient gas atoms to soak up the incident ionising photons. We assume an electron temperature $T_{\rm e} \simeq 10^4$ K, as expected for gas photoionised by stellar sources, for which the Case B hydrogen recombination coefficient is $\alpha_{\rm B} \simeq 2{\cdot}6 \times 10^{-13}(10^4/T_{\rm e})^{0{\cdot}75}$ cm^3 s^{-1}. At these temperatures, collisional ionisation processes are negligible. In this case, the column recombination rate in equilibrium must equal the normally incident ionising photon flux, $\alpha_{\rm B} n_{\rm e} N_{\rm H}^+ = \varphi_i$, where φ_i is the rate at which Lyc photons arrive at the cloud surface (photons cm^{-2} s^{-1}), $n_{\rm e}$ is the electron density and $N_{\rm H}^+$ is the column density of ionised hydrogen. The emission measure is just $\varepsilon_m = \int n_{\rm e} n_{\rm H}^+ \, {\rm d}l = n_{\rm e} n_{\rm H}^+ L$ cm^{-6} pc, where L is the thickness of the ionised region. The resulting emission measure for an ionising flux φ_i is then $\varepsilon_m = 1{\cdot}25 \times 10^{-2} \varphi_4$ 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 idealised model for predicting the Hα emission measure at the distance of the Magellanic Stream. The ionising stars are assumed to be isotropic emitters confined to a thin disk in the xy plane (or the XY plane in Galactic Coordinates, e.g. Figure 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 $f_{\rm d}$ (in units of erg cm^{-2} s^{-1} Hz^{-1}) from ionising disk sources

https://doi.org/10.1071/AS97059 Published online by Cambridge University Press

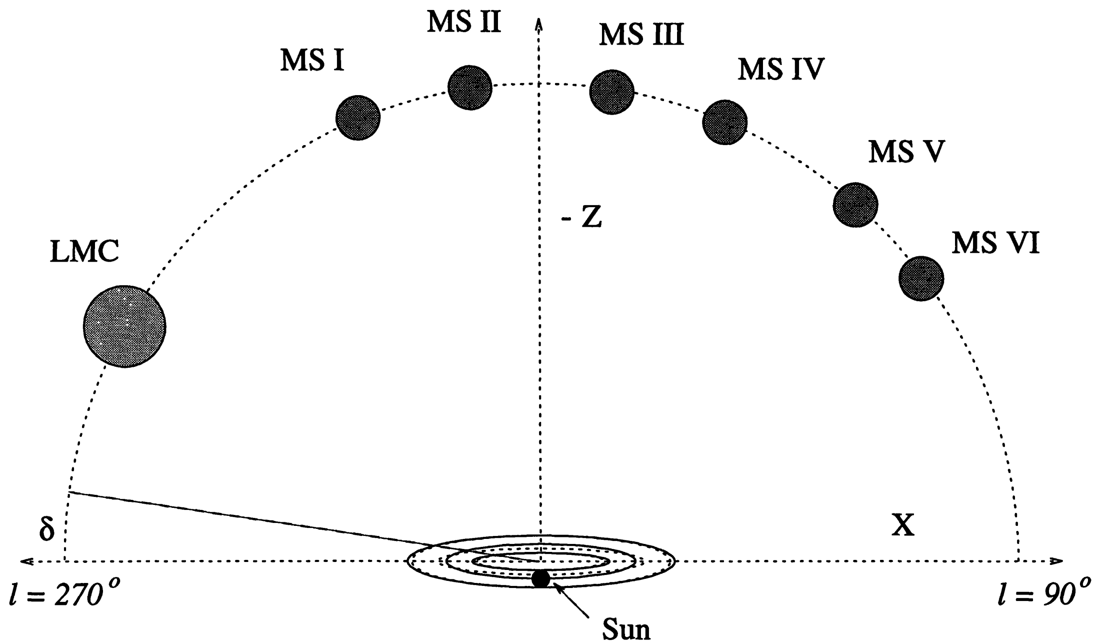

Figure 1—An illustration of the LMC and the dominant clouds in the Magellanic Stream (Mathewson & Ford 1984). The LMC and the Stream have been projected onto the Galactic XZ plane. We have ignored small projection errors resulting from our vantage point at the Solar Circle. The angle δ is measured from 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 $l = 285°$.

with specific intensity ζ_ν through a solid angle dΩ is

$$f_{\rm d} = \int \zeta_\nu \ {\rm d}\Omega = \int \zeta_\nu \ \cos\theta \ {\rm d}A(r,\phi)/R^2 \,, \quad (1)$$

where ${\rm d}A = r \ {\rm d}r \ {\rm d}\phi$ and

$$R = x_0^2 + z_0^2 + r^2 - 2x_0 r \cos\phi \,. \quad (2)$$

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 ionising photon flux from the disk (in units of photons cm^{-2} s^{-1}) is

$$\varphi_{\rm d}(r,\phi) = \int n_{\rm d}(r,\phi) \ \cos\theta \ {\rm d}A(r,\phi)/R^2$$
$$= \int {\rm d}\sigma(r,\phi)\cos\theta/R^2 \,, \quad (3)$$

for which $n_{\rm d}$ 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 ${\rm d}\sigma' = e^{-\tau_{\rm LL}(r,\phi)} \ {\rm d}\sigma$. For a disk population of OB stars, we consider an axisymmetric exponential disk with scale length $r_{\rm d}$, $n_{\rm d}(r) = n_0 e^{-r/r_{\rm d}}$. We adopt a radial scale length of $r_{\rm d} = 3{\cdot}5$ kpc (Kent, Dame & Fazio 1991) and all integrations are performed out to 25 kpc in radius since there is some evidence for faint H$_{\rm II}$ regions at these large radii (de Geus et al. 1993). Vacca, Garmany & Shull (1996) have compiled a list of 429 O stars within 2·5 kpc of the Sun from which they determine an ionising surface density of $n(r_\odot) = 3{\cdot}74 \times 10^7$ 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 $r_\odot = 8{\cdot}0 \pm 0{\cdot}5$ kpc. Thus, from equation (1), we derive $n_0 = 3{\cdot}7 \times 10^8$ phot cm^{-2} s^{-1}.

3 Photoionisation of the Magellanic Stream

The Stream lies along a great arc which extends for more than 100° (e.g. Mathewson, Cleary & Murray 1974). Figure 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 XZ plane, originating from the Lagrangian point between the LMC and SMC. The Cepheid distance moduli indicate that for the LMC $(m - M)_0 = 18{\cdot}47 \pm 0{\cdot}15$, which implies a distance of 49·4±3·4 kpc (Feast & Walker 1987); for the SMC, $(m - M)_0 = 18{\cdot}83 \pm 0{\cdot}15$, 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

https://doi.org/10.1071/AS97059 Published online by Cambridge University Press

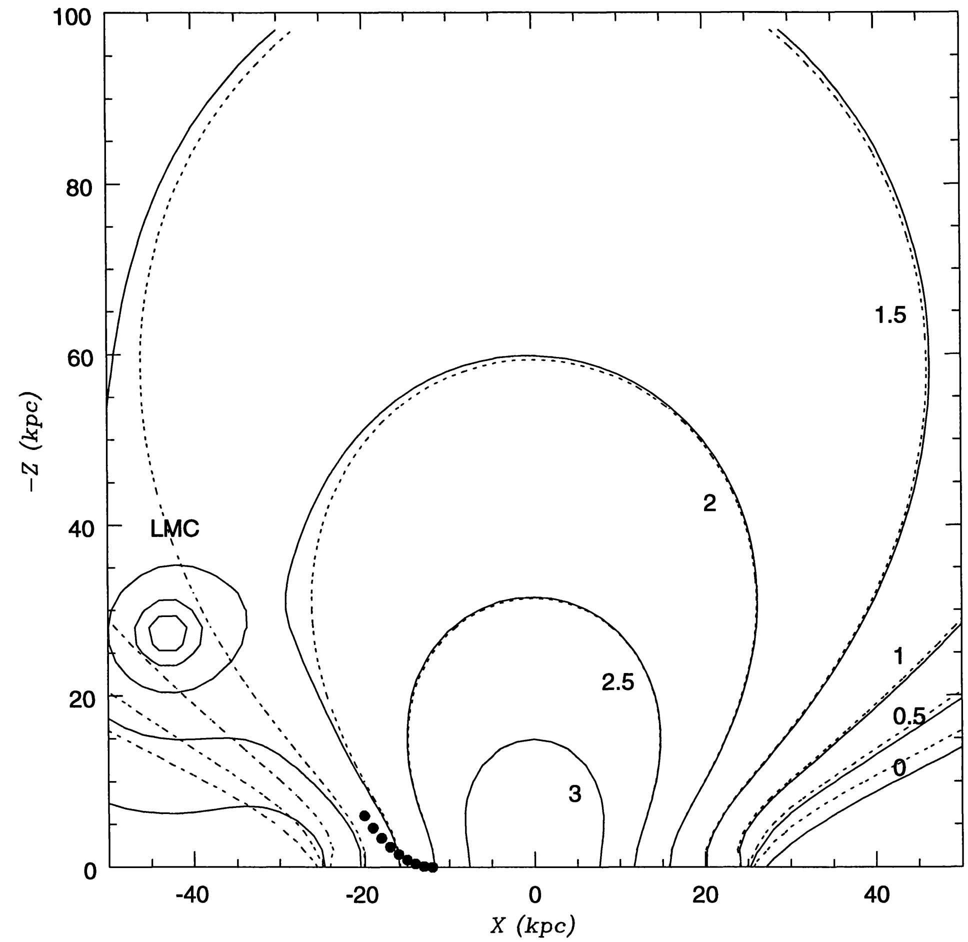

Figure 2—Meridional plot showing the probable contribution of the LMC to the opaque-disk halo radiation field (solid lines). The dotted lines are for the opaque-disk model in Figure 3. The position of the LMC in Galactic coordinates lies within 2 kpc of the plane $Y = 0$ (Fujimoto & Sofue 1976). The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

focal point (e.g. Lin, Jones & Klemola 1995). Our model is consistent with the distance measured by Gardiner, Sawa & Fujimoto (1994) towards MS VI, but not with the much smaller value of 20 kpc determined by Moore & Davis (1994).

In Figure 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) $\times10^4$ phot cm^{-2} s^{-1} (Figure 3). From our earlier equation the expected ε_m values are (9·0, 2·7, 1·3) cm^{-6} pc, or equivalently, (18, 5·4, 2·6) $\times10^{-18}$ erg cm^{-2} s^{-1} arcsec^{-2}. The Weiner & Williams (1996) detections along the stream are 370, 210 and 200 milliRayleighs[1] or, equivalently, ε_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 Figure 3 we present the predicted emission measure along the Stream after projecting the clouds into the XZ 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 ionising photons, otherwise the Magellanic Stream would be mostly ionised.* The shape of the ε_m curve gives an independent assessment of the disk opacity, but this is sensitive to departures from a circular

[1] A Rayleigh unit is $10^6/\pi$ phot cm^{-2} s^{-1} sr^{-1} = $2{\cdot}41\times10^{-10}$ erg cm^{-2} s^{-1} sr^{-1} at Hα.

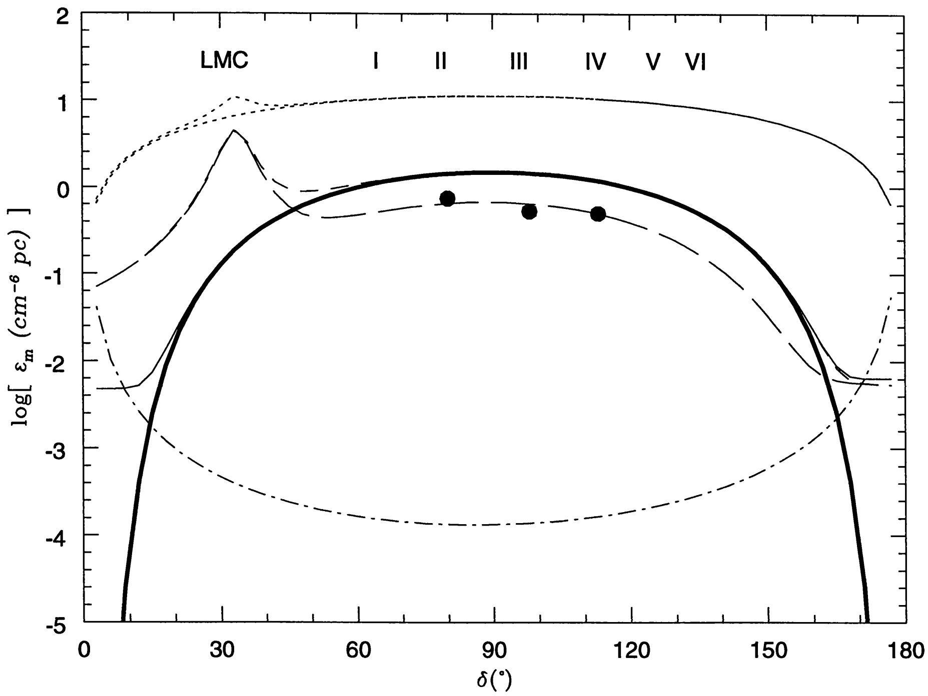

Figure 3 —The predicted Hα emission measure along the Magellanic Stream as a function of δ. The vertical axis has units of log(cm^{-6} pc); these can be converted to log(Rayleighs) by subtracting 0·48. The dotted curves (top) assume an optically thin Galactic disk with and without the LMC ionising field. The solid lines assume an opaque ionising 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 ($\tau_{\rm LL} = 2$) and long-dash ($\tau_{\rm LL} = 2{\cdot}8$) curves. The dot–dash curve is ε_m(Hα) predicted from the upper side of the Magellanic Stream due to the bremsstrahlung halo. The solid points are the ε_m measurements of Weiner & Williams (1996).

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 Figure 3 becomes significantly more boxy at large δ, and possibly even sharply rising towards the edges before turning over. The expected value of ε_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 H I covering fraction.

In the interests of brevity, we do not discuss alternative ionising sources (e.g. shock or halo sources) as these are expected to be entirely negligible. For illustrative purposes only, we include the expected ionisation from the LMC and halo bremsstrahlung in Figure 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 2×10^6 K (0·2 keV). The LMC is treated as a point source radiating 5×10^{51} ionising 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 ionisation. The LMC radiation field is not expected to substantially ionise the Magellanic Stream (MS I–VI) although, presumably, it has a major impact on the outer parts of the Milky Way in the direction $l = 270°$ (see Figures 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 ionising field from the Galactic halo. If the outer warp in the H I disk is not severe ($\leq 10°$ from centre to edge), the ionisation of cold gas at large radius should be dominated by the cosmic UV background. The current 2σ upper limit on the flux, $\varphi_4 = 3{\cdot}8$ (cf. Bland-Hawthorn 1997), indicates that the cosmic background is expected to produce an equivalent emission measure less than $\varepsilon_m = 0{\cdot}05$ cm^{-6} pc.

In summary, for a mean Stream distance of 55 kpc, if $\kappa = 1$, the Hα detections indicate $\tau_{\rm LL} \approx 3$ perpendicular to the Galactic disk such that only 5% of the ionising radiation from the disk escapes into the halo. Notably, Domgorgen & Mathis (1994) have obtained the same result using an entirely different

https://doi.org/10.1071/AS97059 Published online by Cambridge University Press

approach. While OB stars should dominate the ionisation balance, just how the ionising 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).

Acknowledgments

JBH thanks JILA and the University of Colorado for their hospitality during the early stages of this work, and Gary da Costa for important references. We gratefully acknowledge useful comments from J. R. Dickey and an anonymous referee.

Bland-Hawthorn, J. 1997, PASA, 14, 64
Bland-Hawthorn, J., & Maloney, P. R. 1997, ApJ, submitted
Burton, W. B. 1988, in Galactic and Extragalactic Astronomy, ed. G. L. Verschuur & K. Kellerman (Dordrecht: Reidel), p. 295
de Geus, E. J., Vogel, S. M., Digel, S. W., & Gruendl, R. A. 1993, ApJ, 413, 97
Domgorgen, H., & Mathis, J.S. 1994, ApJ, 428, 647
Dove, J., & Shull, M. 1994, ApJ, 430, 222
Feast, M. W. 1988, ASP Conf Ser. 4, ed. S. van den Bergh & C. Pritchet (San Francisco: ASP), p. 9
Feast, M. W., & Walker, A. R. 1987, ARA&A, 25, 345
Ferguson, A. M. N., Wyse, R. F. G., Gallagher, J. S., & Hunter, D. A. 1996, AJ, 111, 2265
Fujimoto, M., & Sofue, Y. 1976, A&A, 47, 263
Gardiner, L. T., Sawa, T., & Fujimoto, M. 1994, MNRAS, 266, 567
Hogan, C. J., & Weymann, R. J. 1987, MNRAS, 225, 1P
Hoopes, C. G., Walterbos, R. A. M., & Greenawalt, B. E. 1996, AJ, 112, 1429
Kent, S. M., Dame, T. M., & Fazio, G. G. 1991, ApJ, 378, 131
Leitherer, C., & Heckman, T. M. 1995, ApJS, 96, 9
Lin, D. N. C., Jones, B. F., & Klemola, A. R. 1995, ApJ, 439, 652
Mathewson, D. S, Cleary, J. D., & Murray, M. N. 1974, ApJ, 190, 291
Mathewson, D. S., & Ford, V. L. 1984, in Structure and Evolution of the Magellanic Clouds, IAU Symp., 108, 125
Miller, W. W., & Cox, D. P. 1993, ApJ, 417, 579
Moore, B., & Davis, M. 1994, MNRAS, 270, 209
Reid, M. 1993, ARA&A, 31, 345
Reynolds, R. J. 1990, in Galactic and Extragalactic Background Radiation, ed. S. Bowyer & C. Leinert (Dordrecht: Kluwer), p. 157
Vacca, W. D., Garmany, C. D., & Shull, J. M. 1996, ApJ, 460, 914
Weiner, B. J., & Williams, T. B. 1996, AJ, 111, 1156

https://doi.org/10.1071/AS97059 Published online by Cambridge University Press