The Galactic Halo Ionizing Field and Hα Distances to HVCs

J. Bland-Hawthorn
Anglo-Australian Observatory, PO Box 296, Epping, NSW 2121, Australia

P.R. Maloney
Center for Astrophysics & Space Astronomy, University of Colorado, Boulder, CO 80309-0389

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. While the distance to the Magellanic Stream is uncertain, the observed Hα emission is most plausibly explained by photoionization due to hot, young stars. Our model requires that the mean Lyman-limit opacity perpendicular to the disk is \( \bar{\tau} \approx 3 \), assuming the covering fraction of the resolved clouds is close to unity. Within the context of this model, it now becomes possible to determine distances to high velocity clouds, and the 3D orientation of the Magellanic Stream. Here, we discuss complications of the model (e.g., porosity, topology), future tests, ongoing improvements, and the importance of Hα limb brightening from surface ionization. More speculatively, we propose a direct experiment for locating an HVC in 6-dimensional phase space above the Galactic plane.

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

1. Introduction

After two full days at this first ever High Velocity Clouds (HVCs) workshop, there were portents that we are on the threshold of a Renaissance in the study of the interstellar and the intergalactic medium. Space-borne UV spectroscopy reveals nearby counterparts to distant Ly\( \alpha \) clouds (Sembach; see Sembach et al. 1998). HVCs with high HI columns are now routinely detected in Hα emission (Tufte, Reynolds & Haffner 1998; Bland-Hawthorn et al. 1998). The exquisite HIPASS observations of the Stream reveal great complexity (Putman; see Putman et al. 1998). Blitz proposed a far-reaching scenario that many HVCs are hundreds of kiloparsecs away, and are evidence for debris from the formation of the Local Group.
In collaboration with Putman & Gibson, we find that most, if not all, resolved gas clouds observed to date—with a mean column density higher than $10^{19} \text{ cm}^{-2}$—can be detected in sensitive H$\alpha$ observations. Of course, this statement comes with caveats emptor since the expected threshold for which this holds true is an order of magnitude lower. However, there was widespread recognition of the importance of direct H$\alpha$ detections of HVCs (for a review, see Wakker & van Woerden 1998; Tufte et al. 1998; Bland-Hawthorn et al. 1998). We shall argue that H$\alpha$ detections towards high column HI structures can be converted to distances if these clouds are situated in the halo of the Galactic ionizing field. If correct, H$\alpha$ detections and non-detections are set to revolutionize the field.

Here, we discuss potential pitfalls of the distance model, future improvements, and complicating factors like cloud topology and covering fraction.

2. The escape of ionizing photons from the Galaxy

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; Greenawalt et al. 1998). Broadly speaking, if the optical depth at the Lyman limit is $\bar{\tau}$, these observations require $\bar{\tau} \approx 1$ on scales of $\sim 100$ pc. The vertically extended Reynolds layer requires that $\bar{\tau} \approx 2$ to explain the observed line emission (Reynolds 1990). At the distance of the Magellanic Stream, we have shown (Bland-Hawthorn & Maloney 1999) that the observed H$\alpha$ emission measures (Weiner & Williams 1996, hereafter W$^2$) are consistent with ionization by the Galactic disk providing 6% of the ionizing radiation ($\bar{\tau} \approx 3$ perpendicular to the disk) escapes into the Galactic halo. The influence of this residual radiation is easily detected with sensitive H$\alpha$ observations out to great distances (100 kpc or more) from the Galaxy.

3. The shape of the halo ionizing field

The emission measure $E_m$ 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). If the strength and direction of the radiation field is known, the observed H$\alpha$ emission from the surface of the cloud can be used to determine the cloud distance. This assumes that the covering fraction ($\kappa$) and the projected cloud topology — seen by the ionizing photons — is known and that there are sufficient gas atoms to soak up the incident ionizing photons. In a spate of recent papers (Bland-Hawthorn & Maloney 1997, 1999; Maloney & Bland-Hawthorn et al. 1998), we develop an idealized, opaque disk + halo model for predicting the H$\alpha$ emission measure at an arbitrary point within the Galactic halo. The reader may investigate this model through the pgperl web tool at
Fig. 1 shows how the surfaces of constant ionizing flux (in units of $\varphi_4$, i.e., $10^4$ ionizing photons cm$^{-2}$ s$^{-1}$) are highly elongated, producing the appearance of ‘ionization cones’, in the direction of the spin axis above an opaque disk. This is consistent with the constant ionization seen along extended filaments perpendicular to the Galactic disk (Haffner, Reynolds & Tufte 1998) and starburst disks (e.g., Phillips 1993; Shopbell 1996). The dotted lines illustrate the possible influence of the LMC. Without the LMC, the ionizing field is axisymmetric. For clouds that lie within 10 kpc or so of the disk plane, the model needs to include the known positions of the spiral arms (see below).

$\tau = 3$

Fig. 1. The Galactic halo ionizing field. The coordinates are with respect to a plane perpendicular to the Galactic disk (with the Galactic centre at the origin) at a constant galactic azimuth angle ($75^\circ$, $255^\circ$). The dotted lines show the ionizing flux ($\varphi_4$) due to the galactic disk; the solid lines include the contribution from the LMC ($1.5 \times 10^{52}$ phot s$^{-1}$). The opacity of the HI disk (shown in half tone) has been included. The contours, from outside in, are for log $\varphi_4 = 1, 1.25, 1.5, 1.75, 2, 2.25, 2.5, 3$ phot cm$^{-2}$ s$^{-1}$. The minor contribution from the Galactic corona is omitted.
4. Tests of the Galactic ionizing field model

Our working model for the Magellanic Stream Hα detections requires independent confirmation. The disk-halo ionization model implicitly assumes that O (and B) stars dominate the halo energetics out to great distances. For the model to survive, it must pass a number of important tests.

4.1. Dilute & shock ionizing radiation fields

The emission line diagnostics for stellar photoionization are fairly well understood (Fig. 2). The ionizing spectrum of an O star drops precipitously beyond 20 eV (Kurucz 1979; Vacca et al. 1996), with 10% of the energy emerging in the interval 24.6 eV to 54.4 eV, and only a tiny fraction appearing beyond the He II edge at 54 eV (however, cf. Schaerer & de Koter 1997). This tapering energy band is only able to excite a limited range of optical diagnostics in the strong field limit, with an even more restricted list in the weak field limit.

Large-scale shocks as a source of ionization are an attractive prospect, particularly in light of the spectacular bow-shock morphology at the head of, and in small knots along, the Magellanic Stream (Mathewson & Ford 1984). However, such a morphology is much less evident in the HIPASS survey (Putman et al. 1998). The shocks one anticipates in conventional drag models are unlikely to produce significant amounts of Hα emission. The radiative regions in shocks are in pressure equilibrium with the external gas (Sutherland & Dopita 1993) such that

\[ n_A v_{\text{LMC}}^2 \approx n_S v_S^2 \]

where \( n_A \) is the ambient density, \( v_{\text{LMC}} \) is the speed of the Stream in the frame of the Galaxy, \( v_S \) and \( n_S \) are the shock velocity and the post-shock density. We adopt a coronal density of \( n_A \approx 10^{-4} \), the maximum allowed by pulsar dispersion measures; at the head of clouds MS II–IV, the volume-averaged atomic density from the HIPASS observations is in the range \( n_S = 0.1 \)–1 cm\(^{-3}\). The \( E_m \) values quoted by Weiner & Williams produce electron densities in our range for any reasonable path length. Proper motion studies indicate that the total Galactocentric transverse velocity for the LMC is \( v_{\text{LMC}} = 213 \pm 49 \) km s\(^{-1}\) (Lin, Jones & Klemola 1995). The predicted shock velocities arising from the Stream dynamics are only a few km s\(^{-1}\), which are far too small to ionize hydrogen.

There exists another class of shock models, not discussed by Weiner & Williams, which could conceivably ionize the clouds. Gas heated by supernovae can puncture the cold disk and escape into the halo (e.g., Norman & Ikeuchi 1989). The hot halo gas may form a galactic wind, a hydrostatic atmosphere around the Galaxy or, more likely, it may eventually cool, recombine and descend onto the disk, establishing a galactic fountain (Shapiro & Field 1976; Bregman 1980; Houck & Bregman 1990; Shapiro & Benjamin 1994). In this picture, the Galactic fountain is largely responsible for the hot corona and may possibly explain HVCs as material involved in the circulation process (but see Wakker & van Woerden 1991). The cool, descending gas of the galactic fountain would be detectable at anomalous velocities in 21 cm emission. Theoretically, the maximum velocity of gas streaming to the disk is roughly 100 km s\(^{-1}\). High apparent velocities are predicted only for distant clouds, because of the particular mechanism of acceleration in combination with projection effects induced by...
galactic rotation. Thus, the model can explain the existence of gas with velocities up to 200 km s$^{-1}$, but not if it is generally nearby.

Fig. 2. The dependence of five important line diagnostics on the ionization parameter $U = \phi_i/cn_H$. The solid lines are radiation bounded models where all ionizing photons are soaked up by the gas. Also shown are matter bounded models where the slab has been truncated at 1, 2, 5, 10 and $20 \times 10^{18}$ cm$^{-2}$.

4.2. Spectral diagnostics

The importance of detecting HVCs in more than one emission line cannot be overstated. Simultaneous detections have already been achieved with both Fabry-Perot and faint object spectrographs (Bland-Hawthorn et al. 1998; 1999). For example, a fountain is expected to produce strong low ionization lines (\[\text{OII}\], \[\text{NI}\], \[\text{OI}\], etc.) due to shocks and perhaps metal-enriched material from the central disk (Shapiro & Benjamin 1993). Unfortunately, these are the same diagnostic lines produced by dilute stellar photoionization, but multi-line spectroscopy remains a crucial probe of the radiation field. The discovery of, say, strong \[\text{OIII}\] emission anywhere along the Magellanic Stream would indicate that some unforeseen ionization/heating mechanism is at work, and would cast doubt on our disk ionization model.

For a gas with known metal abundances, line diagnostics can be used to constrain the ionization parameter $U = \phi_i/cn_H$. The few HVCs with constrained metallicities appear to have abundances no more than one third of solar (de Boer & Savage 1984; Blades et al. 1988). The most commonly used line ratios, when plotted as a function of $U$, are characterized by bell-shaped curves with different first and second moments (see Fig. 2). The decline at high and low $U$ marks the change in electron temperature and the increasing importance of higher and lower ionization states, respectively. Detailed line ratios have been computed
for a range of ionizing sources, including shocks, non-thermal power laws, and hot young stars observed through an opaque medium (Mathis 1986; Veilleux & Osterbrock 1987; Sokolowski 1992, 1995; Sutherland & Dopita 1993; Shapiro & Benjamín 1993). As Fig. 2 shows, a complicating factor is whether the gas clouds are matter or radiation bounded.

The limited broadband spectroscopic work to date on HVCs implicates dilute photoionization. We did not detect [OIII] towards MS II A or the Smith Cloud, and in the latter study, [NII]/Hα was observed to be of order unity (Bland-Hawthorn et al. 1998; Bland-Hawthorn et al. 1999). Furthermore, a recent spectrum with the MSO 2.3m double beam spectrograph shows evidence for a similar enhancement of [SII]/Hα towards MS II A. Taken together with the close match between the Hα and HI kinematics, the spectral diagnostics (Fig. 2) are suggestive of static photoionization of cloud surfaces in a very dilute, ionizing field.

5. Hα distances to HVCs

We anticipate that HVCs will be detectable in sensitive Hα observations to distances of more than 100 kpc. Several HVCs have now been detected in Hα emission (Kutyrev & Reynolds 1989; Münch & Pitz 1990; Bland-Hawthorn et al. 1998; Tufte, Reynolds, & Haffner 1998), at levels of ≈ 0.1 – 0.3 R, in addition to the W2 Magellanic Stream detections. A detailed discussion of the use of Hα observations as a distance indicator for HVCs is presented in Bland-Hawthorn et al. (1998). Here we simply note that: (1) although there are likely to be difficulties with inferring the distances for clouds within z ≲ 10 kpc above the plane, due to structure in both the absorption and ionizing photon emissivity on smaller scales, our ionizing field model predicts the distances of the M and A complexes (as observed by Tufte et al. 1998) to within a factor of two; (2) by mapping the emission measure along the Magellanic Stream, it will be possible to infer both the actual three-dimensional geometry of the Stream with respect to the Galactic plane, and the value of f_esc for the LMC, which may produce a modest but measurable increase in the emission measure in the Stream near the LMC.

6. Distance uncertainties

6.1. Primary calibrators

In practice, we do not doubt that the uncertainties in Hα distances to HVCs are large (i.e., factors of a few), particularly for clouds close to the plane. Our models assume that the covering fraction of the HI slab is unity as seen by the ionising photons, and that the Galactic dust and ionising sources are smoothly distributed. But we would argue that crude distances, and even the ability to distinguish between ‘nearby’ (detection) and ‘far away’ (non-detection), is a major advance. Even without a reliable primary distance calibrator, there is a great deal to learn from relative distance measurements, although this assumes that clouds possess the same basic structure and topology regardless of size. The Magellanic Stream may constitute the best prospect for a primary calibrator, if the distance to a particular cloud along the Stream could be determined inde-
pendently and unambiguously. In the foreseeable future, the prospects for an
independent calibration look grim.

6.2. Porosity

A problem that has haunted us for several years now refuses to go away:

For a sheet of gas lying in the plane of the sky, can an observer de-
termine experimentally what fraction of the projected area is opaque
to Lyman limit photons?

This problem is intimately linked to a concern raised by Bregman during the
meeting. The HI maps of Mathewson & Ford (1984) give the impression that
atomic gas forms a continuous screen along the Stream with a column density
exceeding the Lyman limit threshold. If this was true, then the weakest Hα
measurements, or even the non-detections, are more relevant for normalizing
the Galactic ionizing field; the stronger detections would require an independent
source.

The HI covering fraction \( \kappa \) remains the major stumbling block to using
clouds as sensitive probes of the ambient radiation field. Simply put, this is the
fraction of area within unit solid angle that is taken up by gas with a hydrogen
column density sufficient to absorb ionizing photons below a specific energy.
Since the absorption cross-section declines rapidly with energy, we shall restrict
our definition to photons with energy less than or equal to 250 eV.

The covering fraction seen from Earth is much less important than the
covering fraction seen by the ionizing photons. A case in point is the HI 1225+01
cloud discovered by Giovanelli & Haynes (1991) in the Local Supercluster. This
has been used by various authors (e.g., Vogel et al. 1995) to set limits on \( \Phi^0 \),
the metagalactic UV flux. However, the structure is now thought to be flattened
and highly inclined to the line of sight (Chengalur, Giovanelli & Haynes 1995).

To be sure of even the global structure, an HI screen should have its longest
dimensions close to the plane of the sky. Even under ideal circumstances, it is dif-
ficult to determine \( \kappa \) unambiguously. A smooth HI distribution gives essentially
no structural information on scales smaller than the beam size. A large variance
in the structure (e.g., Dickey 1979) compared to the mean HI column might
imply a lumpy distribution although temperature fluctuations and/or kinematic
variations can produce the same effect. HI clouds may comprise dense cores and
an ambient diffuse component (e.g., Ferrara & Field 1993). It may be possible
to use extended baseline, 21 cm spectroscopy to resolve the clumps on small
(\( \sim 0\prime.1 \)) scales. A comparison with single dish observations will establish whether
the remaining gas is opaque to ionizing photons if smoothed over the remaining
solid angle between the dense clumps.

There has been extensive work on Galactic HI clouds by looking for ab-
sorption towards background radio continuum sources on small angular scales
(Payne, Salpeter & Terzian 1983; Colgan, Salpeter & Terzian 1990). Direct ob-

\(^1\)\( \kappa \) is sometimes referred to as the covering factor or the beam filling fraction. The covering
fraction and volume filling fraction \( f \) are linearly related in the limit of small \( \kappa \), although this
no longer holds true as \( \kappa \) and \( f \) approach unity.
servations of the HI emission are complicated by the need for both radio interferometers and single dish observations (Crovisier & Dickey 1983). In single dish observations, it is straightforward to produce an autocorrelation function (ACF) of the observations. But whether this constitutes a useful probe of statistical variations is doubtful, particularly with the regular occurrence of side-lobe contamination. Unfortunately, most authors (e.g., Crovisier & Dickey 1983) publish the ACF after subtracting the mean and normalizing to unit variance without stating these quantities. Alternatively, interferometers measure the complex visibility function along particular tracks in $u−v$ space, which can be converted to a fringe amplitude and therefore a power spectrum. The zero spacing is never observed which complicates the process of normalizing the higher resolution interferometric data with single dish observations.

For Galactic HI clouds, ROSAT HI shadows may provide the best clues, and appear to indicate a covering fraction close to unity (Snowden et al. 1991; Burrows & Mendenhall 1991). Here, a comparison is made between IRAS or HI observations and ROSAT observations at each independent beam position. Since soft X-ray emission is absorbed by neutral atomic gas, the known $N_{\text{HI}}$ (for an assumed dust to gas ratio) can be compared with the fraction of X-rays that gets through compared to the background. The method has its weaknesses: (i) the slope of the X-ray spectrum is assumed, (ii) the HI observations are smoothed to the relatively poor beam size of the ROSAT observations.

More speculatively, by analogy with ROSAT shadows, it may be possible (cf. Gould & Sciama 1964) to determine $\kappa$ for gas clouds projected against hot cluster gas or even attenuation of unresolved X-ray sources in deep ROSAT observations (Fabian & Barcons 1992). At optical wavelengths, there are only a few quasars per square degree bright enough for line spectroscopy. Deep Keck images at $B=26$ mag arcsec$^{-2}$ show that up to one million galaxies are to be found within each square degree (Smail et al. 1995). A comparison of the number counts observed through an HI cloud compared to an offset field could be used to establish the mean opacity through the disk. However, the faintest sources may be highly clustered on large scales which would complicate the analysis.

Detailed mapping of HI clouds in several emission lines (e.g., Fig. 2) may go some way to answering the question posed at the beginning of this section. It is difficult to identify a rigorous, definitive test: the eventual resolution may come down to a circumstantial body of evidence. There is, however, another motivation for optical line maps, as we now discuss.

### 7. The importance of limb brightening

Any form of limb brightening observed in optical/IR emission lines near HVCs, and HI structures in general, has important ramifications. In Fig. 3, the expected contrast level $C$ is given roughly by

$$C \sim 2 \left( \frac{dR}{B} \right)^{0.5} \left( \frac{R}{B} \right)^{0.5}$$

where $dR$ is the depth of the ionized layer in parsecs, $R$ is the radius of curvature at the ionized surface, and $B$ is the beam size of the spectrograph. The skin depth can be estimated crudely from (i) the observed emission measure ($dR \sim \ldots$)
along a sight line through the middle of the cloud, (ii) the inferred radiation field \( dR \sim 10^{-1.0} \varphi_{A} n_{e}^{-2} \), or (iii) the inferred ionization parameter \( dR \sim 10^{6.3} \mathcal{U} n_{e}^{-1} \), assuming the mean density has not changed after ionization. Clearly, the degree of contrast will depend on the beam size, \textit{i.e.}, \( 1^{\circ} \), WHAM; \( 0.5^{\circ} \), Las Campanas; <\( 0.15^{\circ} \) for most other groups. As many clouds as possible should be observed by both small and large beams.

\[ \text{Fig. 3. The instrument beam size } B \text{ projected onto the limb brightened edge of a high velocity cloud.} \]

The presence of limb brightening can tell us many things about the cloud and the ionizing source:

- The cloud has a sharp edge and is dense enough to stop ionizing photons within a short stopping length.
- The volume filling fraction \( f \) of the cloud is finite, say, \( f > 10^{-2} \), as we demonstrate with the fractal model below.
- The brightest H\( \alpha \) emission may trace the overall morphology of the illuminated cloud.
- If the limb brightening is restricted to one side of the cloud, this gives the direction of the dominant ionizing source, or the direction of motion in the case of shocks; the emission measure from the opposite side provides a sensitive gauge of the metagalactic UV flux.
- It is possible that the degree of contrast alone is a crude distance indicator, \textit{e.g.}, WHAM is only expected to see high contrasts for nearby clouds.

8. **Topology: complex clouds and cloud complexes**

A major concern is that clouds do not constitute simple structures on the scale size of the beam. This is a well known problem in atmospheric physics, particularly in studies of terrestrial clouds. Wakker raised the matter of how HI structures should be classified. Statistical estimators (\textit{e.g.}, N-point correlators) are sensitive to gaussian fluctuations, multifractals, Markov chains, hierarchies, random walks, and so on. The choice of estimator largely reflects the physical process under study, which is largely unknown for structure in HI surveys. Wavelet analysis and topological measures (\textit{e.g.}, Minkowski functionals) have
been shown to work well with noisy pixelated data (e.g., Hobson, Jones & Lasenby 1998).

Fig. 4. A fractal cloud of dimension $D = 3$ comprising 8000 cells, each with column density $3 \times 10^{17} \text{ cm}^{-2}$, ionized by an isotropic background. The projected column density of the cloud (left) shows many volume brightened regions, compared to the projected emission measure (right) which shows limb brightening on the smallest and largest scales.

A common starting point is to adopt a ‘building block’ associated with the simplest detectable structure at high resolution. More specifically, in eight pointings with our 10′ TAURUS beam towards clouds identified by HIPASS, Hα emission is always detected along sight lines where the beam-averaged $N_H > 10^{19}$ cm$^{-2}$. (For the time being, we choose to overlook the fact that this threshold is an order of magnitude higher than expected for UV photons.) Let us suppose that columns higher than our threshold arise from compact cloud structures within the Stream.

We have examined cloud geometry and porosity for a range of distributions (e.g., fractals; see Pfenniger & Combes 1994). The fractal cloud in Fig. 4 has an inverse square density law, and the surface of the cloud is irradiated by an isotropic ionizing background. Our simulations produce clouds that are roughly spheroidal, although this is not a restriction (Voss 1985). We find that ‘volume brightened’ clouds at 21 cm, with large filling factors, can exhibit ‘limb brightening’ at Hα on arcminute scales. Note that the HI cloud appears to have a dense core and an outer envelope (cf. Ferrara & Field 1994).

In Fig. 4, the left and right maps appear to be inversely related, but this is only a property of some specific fractal models, and is not generally true. Imagine a sphere which we begin to populate uniformly but sparsely with optically thick cloudlets. The projected Hα emission measure and HI column density are both volume brightened. As the number of cloudlets increases, we pass through an

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2 We adopt ‘volume brightened’ as the antonym of ‘limb brightened’ to indicate that spheroidal clouds appear brighter through the centre due to the larger column.
interesting transition where the Hα emission is now uniform over the cloud while the HI remains volume brightened. This arises because the outer cloudlets partially shadow the inner cloudlets from the external field. In the limit of large $f$, the Hα emission becomes limb brightened, in contrast to the HI which remains volume brightened.

For a large set of matched HI and Hα pointings, much can be learnt from simple 2D histograms with axes $(N_H, E_m)$. For example, any sort of relation where $E_m$ is proportional to some positive power of $N_H > 3 \times 10^{17}$ cm$^{-2}$ would indicate $\kappa \ll 1$. Our fractal clouds produce histograms with exponential slope inversely related to $N_H$, where the slope is related to $D$, which can be understood analytically. A complete theoretical analysis must consider clouds both near and far from the ionizing source and the observer. The surface ionization of clouds close to the disk will be highly susceptible to the poorly known distribution of dust and UV sources, and maybe shadowing of the disk by other HVCs.

There may be useful information within individual Hα exposures. For clouds detected at the level of 1R, it should be possible to obtain useful detections after dividing a single exposure into discrete segments. Since the radiation field at large galactocentric distances changes smoothly, large Hα fluctuations across individual clouds and along the Stream are indicative of clumpiness. If all clouds were identical in structure, the mean Hα signal and Hα variances constitute independent distance estimators.

In summary, the Hα variances, the degree of limb brightening and the mean flux level, taken together, are needed to improve the reliability of the Hα distance method.

9. Improvements to the Galactic halo ionization model

The Galactic halo ionization model is discussed in detail elsewhere (q.v., Bland-Hawthorn et al. 1998). In the long term, its general acceptance will be intimately linked to the interpretation of the Magellanic Stream Hα detections. In the short term, there are two burning issues to be addressed: (i) the escape of UV photons from the LMC (which bears on our derived $f_{esc}$ for the Galaxy), and (ii) the incorporation of spiral arms into the disk model to improve distances to clouds within 10 kpc of the Galactic plane.

9.1. The escape of UV photons from the LMC

The Magellanic Stream and the Magellanic Clouds appear to share a common link. The current understanding is that the Clouds are in a close binary orbit about the Galaxy (Murai & Fujimoto 1980) and are engulfed in a common HI envelope (Kerr et al. 1954; Westerlund 1990). The Magellanic Stream appears to extend from the Lagrangian point between the Clouds and is observed to circle the Galaxy in an inclined plane with respect to the disk (although see Lin, Jones & Klemola 1995). The LMC has several highly active star forming regions, particularly regions of very recent star formation (Shapley III) and of ongoing star formation (30 Doradus). Fujimoto & Sofue (1976) give a specific position for the LMC in Galactic coordinates, $(X, Y, Z) = (-43, 2, -28)$ kpc, which is close to the plane $Y = 0$. In Fig. 5, we show the influence of the LMC
on the poloidal radiation field in the X-Z plane passing through the Galactic Center.

![Graph](image)

**Fig. 5.** (a) The predicted emission measure along the Stream as a function of $\delta$, defined in (b). The vertical axis has units of log(cm$^{-6}$ pc), equivalent to log(Rayleighs) after subtracting 0.48. The top curves assume an optically thin Galactic disk with (dashed line) and without (solid line) the LMC ionizing field. For the lower curves, the solid lines assume an opaque ($\bar{\tau} = 2.8$) ionizing disk with (thin line) and without (thick line) a bremsstrahlung halo; the LMC contribution is shown by the long-dashed curve (using the same model as Fig. 1). The dot-dash curve is $E_m$(H$\alpha$) predicted for the upper side of the Stream due to the bremsstrahlung halo; the cosmic ionizing background is expected to dominate here. The open circles are the $W^2$ H$\alpha$ measurements.

The basic ionizing requirement of the LMC from combined UV, optical and radio studies appears to be $5 \times 10^{51}$ phot cm$^{-2}$ s$^{-1}$. Within a factor of two, this is consistent with OB star counts (Walborn 1984; Parker 1993), radio continuum observations (McGee, Brooks & Batchelor 1972; Israel & Koornneef 1979), and vacuum ultraviolet observations (Smith et al. 1987) of the LMC. However, we note that the total number of ionizing photons produced by the LMC HII regions, spread over a 5 kpc region, may be as high as $1.5 - 3 \times 10^{52}$ phot s$^{-1}$ (Smith et al. 1987). OB star counts around 30 Dor (e.g., Parker 1993) could well underestimate the total ionizing flux by a substantial factor. Kennicutt et al. (1995) suggest that fully one third of the ionizing radiation in the LMC arises from within $0.5^\circ$ of 30 Dor. The ground-based results may suffer from crowding which means that the total number of stars is underestimated.

To examine this, we predict the H$\alpha$ emission along the Stream using a high value for the intrinsic UV flux ($3 \times 10^{52}$ phot s$^{-1}$), and assume that $f_{\text{esc}} = 50\%$. In Fig. 5, H$\alpha$ observations of MS I and MS II are critical for determining the UV escape fraction from the LMC. The dilution of the radiation field should be detectable. This is crucial to determining the 3D orientation of the Leading Arm (Putman et al. 1998) in addition to the Stream. A curious aspect of a substantial flux from the LMC is that this can mimic the appearance of shock ionization by lighting up the front surfaces of the Stream clouds.

If we assume that the trajectory of the Magellanic Stream is described by a circular orbit with a radius of roughly 50 kpc, then these clumps appear to
lie close to the Galactic polar axis extending to positive X values. Toomre (1972) first suggested that the Clouds may have induced the observed warp in the Galactic plane. But we note from Fig. 1 that the LMC could also have a substantial ionizing effect on the cold gas in the plane of the HI disk in the direction $l = 250^\circ - 270^\circ$. In Fig. 1, the HI disk warps towards negative $Z$ values along this axis (Burton 1988, Fig. 7.23). It is plausible that the differences in the extent of the warp along $l = 270^\circ$ compared with $l = 90^\circ$ are due to ionization by the LMC, particularly if the escaping flux is at the higher end of the quoted range.

9.2. Spiral arms

For HVC distances within 10 kpc of the plane, the halo ionization model needs a more realistic distribution of ionizing sources. This would be straightforward if we knew the exact location of all O stars, and the precise dust distribution throughout the Galaxy. At present, we assume that the disk UV field is smoothly distributed; a more realistic model must include a predominant non-axisymmetric component.

Our updated ‘disk-halo’ ionization model links its fortunes to the standard model for determining pulsar distances. Rough distances to pulsars are determined from the dispersion (and scattering) measure due to warm electrons along the line of sight. Early attempts used a smooth distribution of electrons (e.g., Manchester & Taylor 1981) although Lyne, Manchester & Taylor (1985) showed that typical distance estimates have random errors as large as a factor of two. After the inclusion of smooth spiral arms, Taylor & Cordes (1993) predicted that most distances should be good to $\sim 20\%$. This level of accuracy would be somewhat surprising when one examines face-on spirals in the Ultraviolet Imaging Telescope (UIT) database. But the distance model is largely borne out by lower limits derived from pulsar sight lines which show HI in absorption.

The precise positions of spiral arms in the Galaxy are very difficult to determine. Early attempts to locate arms from continuous distributions (e.g., HI) are unreliable. The most reliable methods are those involving compact sources identified from Galactic plane surveys, where follow-up observations determine a velocity. A distance is inferred from the Galactic rotation curve for sources that do not lie towards the Galactic centre. That this works fairly well is seen from comparing HII regions identified in Parkes single dish measurements (with HI absorption velocities) with optical Fabry-Perot velocities (Georgelin & Georgelin 1976). Caswell & Haynes (1987) find that the radio HII regions fall along the same loops in the (galactic longitude, LSR velocity) plane as the optical HII regions. The same spiral arms can be seen in the longitude—velocity diagram of giant molecular clouds (Dame et al. 1987; Dame 1993; Digel et al. 1996).

Knowing the projected distribution of warm electrons is potentially useful. Taylor & Cordes (1993) note that

*Because the tangent directions to spiral arms are directly observable and independent of any distance estimates, they are defined without ambiguity. Maxima in the intensities of neutral hydrogen and thermal radio emission occur at these longitudes precisely because large quantities of interstellar gas, both neutral and ionized, are found along these lines of sight.*
While these can be different due to phase effects across spiral arms (e.g., Rand 1998), the close association seen by Taylor & Cordes suggests that it may be possible to improve HVC distances close to the plane. For our new model, we bypass the need to know either the O star or the dust distribution. We assume only that the non-axisymmetric distribution of free electrons is proportional to the escaping UV flux from local sources.

The observed electron distribution from WHAM maps and pulsar dispersion measures reveal a smooth component (assumed to be axisymmetric) and a non-axisymmetric component. We normalize the total UV budget so that 6% escapes into the halo (Bland-Hawthorn & Maloney 1999), 15–20% escapes into the Reynolds layer (Reynolds 1984; 1987; 1990; 1994), and some fraction of the total (20–60%; Dahlem 1997; Dettmar 1992; Hoopes et al. 1996) is absorbed on scales of several hundred parsecs around the sites of star formation. (The quoted percentages of the total UV budget are not mutually exclusive.) The remaining radiation is reprocessed into low energy (non-ionizing) photons. Thus, we build up a more detailed disk-halo ionization model by scaling to the free electron density distribution of Taylor & Cordes (1993). UIT observations indicate that the outer parts of mid to late type spirals look similar, although the inner parts exhibit a range of behaviour.

10. Future issues

There is a great deal to learn from future emission line (optical/IR) studies of HVCs and HI structures in general. This conference has recognized the importance of obtaining Hα measurements towards HI clouds in order to derive accurate abundances, masses, etc. The authors have shown in a series of papers that HI clouds should be observable well beyond 100 kpc from the Galaxy. The radiation field is sufficiently strong to ionize HI columns as high as 10^{19} cm$^{-2}$. While as much as one third of the sky is covered by HI, it would not be surprising if a similar fraction is in the form of H$^+$. A particularly exciting prospect is to identify dense HI structures that have no Hα counterpart (cf. Blitz et al. 1999). Briggs (1998) and Staveley-Smith (1998, personal communication) note that stellar counterparts are always seen in the vicinity of HI structures, even for the famous Haynes-Giovanelli extragalactic cloud. Huge HI envelopes and tidal structures are observed in close association to galaxies and groups of galaxies. It is surprising that more HI debris is not found near clusters or galaxy groups, unless the gas becomes dispersed and/or ionized.

Finally, we have discussed the potential of Hα detections for obtaining distances to HVCs, and the pitfalls therein. In the appendices that follow, we consider the prospect of seeing scattered light from these same clouds. Indeed, at the risk of being incautious, it is plausible that some HVCs could be pinpointed in 6-dimensional phase space (§A.2). Elsewhere, we show that our AAT/WHT observing campaigns in early 1999 should uniquely distinguish between the competing dynamical models for the Stream (Bland-Hawthorn et al. 1999). A resolution of this longstanding controversy bears on many astrophysical problems.

Acknowledgments. JBH thanks toddler Christian Hawthorn for the squiggles in Fig. 3. At the risk of ageism, we are indebted to J. Caswell for imparting
several decades of experience in identifying HII regions at Parkes. R.N. Manchester, J.M. Chapman, M. Wardle and S. Johnstone provided us with crucial insights.

References

Blades, J.C. et al. 1988, ApJ, 332, L75
Bland-Hawthorn, J. & Maloney, P.R. 1997, PASA, 14, 59
Bland-Hawthorn, J. & Maloney, P.R. 1999, ApJL, Jan 1st issue
Bland-Hawthorn, J. et al. 1998, MNRAS, 299, 611
Bland-Hawthorn, J. et al. 1999, ApJ, in preparation
Blitz, L. et al. 1999, ApJ, in press
Bregman, J.N. 1980, ApJ, 236, 577
Briggs, F. 1998, In The Low Surface Brightness Universe, IAU Coll. 171, Cardiff
Brück, M.T. & Hawkins, M.R.S. 1983, A&A, 124, 216
Burrows, A.N. & Mendenhall, J.A. 1991, Nat, 351, 629
Burton, W.B. 1988, In Galactic & Extragalactic Astronomy, eds. G.L. Verschuur, K. Kellerman, p. 295
Caswell, J.L. & Haynes, R.F. 1987, A& A, 171, 261
Chengalur, J.N., Giovanelli, R. & Haynes, M.P. 1995, AJ, 109, 2415
Colgan, S.W.J., Salpeter, E.E. & Terzian, Y. 1990, ApJ, 351, 503
Crovisier, J. & Dickey, J.M. 1983, A&A, 122, 282
Dahlem, M. 1997, PASP, 109, 1298
Dame, T.M. et al. 1987, ApJ, 322, 706
Dame, T.M., 1993, Back to the Galaxy, ed. S. Holt and F. Verter, (AIP Conf. Proc. 278) (New York: AIP), p. 267.
de Boer, K.S. & Savage, B.D. 1984, A&A 136, L7
Dettmar, R.-J. 1992, Fund. Cos. Phys., 15, 143
de Vaucouleurs, G. 1954, Observatory, 74, 158
Dickey, J.M. 1979, ApJ, 233, 558
Digel, S.W. et al. 1996, ApJ, 458, 561
Dove, J. & Shull, M. 1994, ApJ, 430, 222
Fabian, A.C. & Barcons, X. 1992, ARAA, 30, 429
Ferrara, A. & Field, G.B. 1994, ApJ, 423, 665
Fujimoto, M. & Sofue, Y. 1976, A&A, 47, 263
Georgelin, Y.M. & Georgelin, Y.P. 1976, A& A, 49, 57
Giovanelli, R. & Haynes, M.P. 1989, ApJ, 346, L5
Gould, R.J. & Sciamma, D.W. 1964, ApJ, 140, 1634
Greenawalt, B.E., Walterbos, R.A.M., Thilker, D. & Hoopes, C.G. 1998, ApJ, 506, 135
Haffner, L.M., Reynolds, R.J., & Tufte, S.L. 1998, ApJ, 501, L83
Hogan, C.J. & Weymann, R.J. 1987, MNRAS 225, 1P
Hoopes, C.G., Walterbos, R.A.M. & Greenawalt, B.E. 1996, AJ, 112, 1429
Houck, J.C. & Bregman, J.N. 1990 ApJ 352, 506
Israel, F.P. & Koornneef, J. 1979, ApJ, 230, 390
Jura, M. 1979, ApJ, 227, 798
Kennicutt, R.C. et al. 1995, AJ, 109, 594
Kerr, F.J. et al. 1954, PASA,
Kurucz, R.L. 1979, ApJS, 40, 1
Kutyrev, A.S. & Reynolds, R.J. 1989, ApJL 344, 9
Leitherer, C. & Heckman, T.M. 1995, ApJS, 96, 9
Lin, D.N.C., Jones, B.F. & Klemola, A.R. 1995, ApJ, 439, 652
Lyne, A.G., Manchester, R.N. & Taylor, J.H. 1985, MNRAS, 213, 613
Manchester, R.N. & Taylor, J.H. 1981, AJ, 86, 1953
Mathewson, D.S., Cleary, J.D. & Murray, M.N. 1974, ApJ, 190, 291
Mathewson, D.S. & Ford, V.L. 1984, in Structure & Evolution of the Magellanic Clouds, IAU Symp., 108, 125
Mathis, J. 1986, ApJ, 301, 423
McGee, R.X., Brooks, S.W. & Batchelor, R.A. 1972, Aust. J. Phys., 25, 581
Miller, W.W., & Cox, D.P. 1993, ApJ, 417, 579
Münch, G. & Pitz, E. 1990, In Galactic & Extragalactic Background Radiation, eds. S. Bowyer & C. Leinert, (Dordrecht: Kluwer), 193
Murai, T. & Fujimoto, M. 1980, PASJ, 32, 581
Norman, C. & Ikeuchi, 1989, ApJ 345, 372
Parker, J.W. 1993, AJ, 106, 560
Payne, H.E., Salpeter, E.E. & Terzian, Y. 1983, ApJ, 272, 540
Pfenniger, F. & Combes, D., 1994, A& A, 285, 94
Phillips, A.C. 1993, AJ, 105, 486
Putman, M.E. et al. 1998, Nature, 394, 752
Rand, R.J. 1998, ApJ, 501, 137
Recillas-Cruz, E. 1982, MNRAS, 201, 473
Reynolds, R.J. 1984, ApJ, 282, 191
Reynolds, R.J. 1987, ApJ, 323, 553
Reynolds, R.J. 1990, in Galactic & Extragalactic Background Radiation, eds. S. Bowyer & C. Leinert, (Dordrecht: Kluwer), 157
Reynolds, R.J. 1992, ApJ, 392, L53
Reynolds, R.J. 1994, in Physics of the Interstellar Medium & Intergalactic Medium, eds. A. Ferrara, C. Heiles, C.F. McKee & P. Shapiro.
Schäerer, D. & de Koter, A. 1997, A& A, 322, 598
Sembach, K.R., Savage, B.D., Lu, L. & Murphy, E. 1998, ApJ, in press
Shapiro, P.L. & Benjamin, R. 1991, PASP, 103, 923
Shapiro, P.R. & Field, G.B. 1976, ApJ, 205, 762
Shopbell, P.L. 1996, PhD, Rice University (Texas)
Smail, I., Hogg, D.W., Yan, L. & Cohen, J.G. 1995, ApJ, 449, L105
Smith, A.P., Cornett, D.H., & Hill, R.S. 1987, ApJ, 320, 609
Snowden, S.L. et al. 1991, Science, 252, 1529
Sokolowski, J. 1992, PhD, Rice University
Sokolowski, J., Bland-Hawthorn, J. & Cecil, G.N. 1991, ApJ, 375, 583
Sutherland, R.S. & Dopita, M.A. 1993, ApJS, 88, 253
Taylor, J.H. & Cordes, J.M. 1993, ApJ, 411, 674
Toomre, A. 1972, QJRAS, 13, 266
Tufte, S.L., Reynolds, R.J. & Haffner, L.M. 1998, ApJ, 504, 773
Vacca, W.D., Garmany, C.D. & Shull, J.M. 1996, ApJ, 460, 914
Voss, R.F. 1985, in Scaling Phenomena in Disordered Systems, eds. R. Pynn & A. Skjeltorp, (New York: Plenum Press), p. 1
Veilleux, S. & Osterbrock, D.E. 1987, ApJS
Vogel, S.N., Weymann, R., Rauch, M. & Hamilton, T. 1995, ApJ, 441, 162
Wakker, B.P. & van Woerden, H. 1991, A&A, 250, 509
Wakker, B.P. & van Woerden, H. 1998, ARAA, 35, 217
Walborn, N.R. 1984, in Structure & Evolution of the Magellanic Clouds, IAU 108, 243
Weiner, B.J. & Williams, T.B. 1996, AJ, 111, 1156
Westerlund, B.E. 1990, A&A Reviews, 2, 29
A.1: The Magellanic Stream seen in reflection?

An interesting possibility is that the W² Hα detections arise from the net Hα emission of the Galaxy being backscattered by high latitude dust. Such an explanation would appear to be unlikely. The $R-$band to Hα luminosity for an L∗ Sbc galaxy is in the range 20 to 100, the clouds would be detectable in optical continuum, which they are not to deep broadband limits (de Vaucouleurs 1954; Recillas-Cruz 1982; Brück & Hawkins 1983; Westerlund 1990). The estimated surface brightness is fainter than 27 mag arcsec$^{-2}$. As a further test, a dust-scattered line profile should show the imprint of the galaxy rotation, increasingly so with decreasing galactic latitude. The observed line profiles (Weiner & Williams 1996) appear to be relatively unresolved although the MS clouds are at small polar angles (i.e., large galactic latitudes). Standard dust models of the ISM predict that the grains are more forward scattering at bluer wavelengths (Sokolowski, Bland-Hawthorn & Cecil 1991, Fig. 3), so it is unlikely that another spectral window will improve the chances of detecting scattered light from the Magellanic Stream. However, high velocity clouds closer to the Galactic plane are much more interesting, as we now discuss.

![Fig. 6. Schematic twin horn Hα profiles which could arise from dust reflection in HI structures above the Galactic plane. A simultaneous observation of Hα due to ionization and Hα seen in reflection could be sufficient to pinpoint some HVCs in 6-dimensional phase space above the Galactic plane.](image-url)

A.2: HVCs seen in reflection?

D.F. Malin (1998, private communication) has made a case for dust nebulosity observed towards some, presumably nearby, high latitude clouds. If so, the emission observed in photographic plates surely arises from Galactic continuum light. This raises an intriguing possibility (cf. Jura 1979). Deep Hα detections
towards reflecting HVCs could show emission from both ionization and reflection. The reflected component will show twin horn structure (analogous to single beam HI observations of spiral galaxies) from integrating over the Galactic disk, where the horn asymmetry and FWHM are directly related to the cloud’s 3D position above the disk (see Fig. 6). The systemic velocity $\vec{v}_s$ of the twin horn structure will reflect both the motion of the dust mirror to the Galactic centre $\vec{v}_{gc}$ and the Sun $\vec{v}_s$, i.e., $\vec{v}_o = \vec{v}_{gc} + \vec{v}_s$. If the H$\alpha$ flux due to ionization is well separated from the reflected component, this could conceivably allow us to locate some HVCs in 6-dimensional phase space above the Galactic plane. Observed properties include the direction of a cloud in galactic coordinates, the horn FWHM, the degree of horn asymmetry, the horn offset from the HI velocity, and the H$\alpha$ ionization flux. Additional measurables include the twin-horn line flux and degree of linear polarization which would be difficult, but certainly not impossible, to measure. With these, the distance problem is now overdetermined.