The Galactic Halo UV Field, Magellanic Stream and HVCs

J. Bland-Hawthorn
Anglo-Australian Observatory, PO Box 296, Epping, NSW 1710, Australia

M.E. Putman
Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

Abstract. Significant numbers of high-velocity $\text{H}\,\text{i}$ clouds (HVCs) have now been detected in $\text{H}\alpha$, with a subset seen in low ionization lines (e.g. $[\text{N}\,\text{II}]$). It was originally hoped that the observed $\text{H}\alpha$ strength would provide a distance constraint to individual clouds. This idea requires that a useful fraction ($f_{\text{esc}} > 1\%$) of ionizing photons escape the Galaxy, and that the halo ionizing field is relatively smooth, as we discuss. HVCs which are known to be close to the Sun are $\text{H}\alpha$-bright; the brightest clouds also show enhanced $[\text{N}\,\text{II}]$ emission, in contrast to the Magellanic Stream where the low ionization emission lines are always weak compared to $\text{H}\alpha$. But an acute complication for $\text{H}\alpha$ distances is the apparent $\text{H}\alpha$ brightness of the Magellanic Stream along several sight lines, comparable or brighter than local HVCs. To account for this, we present three possible configurations for the Magellanic Stream and propose a follow-up experiment. If we normalize the distances to local HVCs, some HVCs appear to be scattered throughout the Galactic halo on scales of tens of kiloparsecs.

1. The big picture

At this meeting, it was clear that the intergalactic medium has become a key frontier across a range of disciplines within astrophysics. The equation of state of the IGM is influenced by the spectral energy distribution of the diffuse cosmic UV field. It is therefore unfortunate that the far UV is the most uncertain part of the cosmic spectrum because it is very difficult to measure at any redshift (Henry 1991). It is normally inferred from the ‘proximity effect’ in quasar spectra, or from reprocessed recombination flux, but these bounds are highly uncertain (Kulkarni & Fall 1993). At low redshift, an alternative scheme is to add up the UV escape fraction ($f_{\text{esc}}$) from likely sources, but again the estimates are highly controversial. If $f_{\text{esc}}$ in star-forming galaxies exceeds a few percent, then massive stars probably dominate over black-hole processes in producing the ionizing background (Giallongo, Fontana & Madau 1997).

In this invited review, we present evidence for UV escape from galaxies (§2,3,4). This conference has devoted a special session to high-velocity clouds, and so we use the second half of the paper to discuss the role of $\text{H}\alpha$ distances. If the Galactic halo UV field is sufficiently strong, the observed $\text{H}\alpha$ flux from
Hi clouds can provide crude distance constraints for each cloud (§5). Bland-Hawthorn & Maloney (1999a, hereafter B99a) attempted to derive $f_{\text{esc}}$ indirectly from Hα along the Magellanic Stream, but it now seems that UV from massive stars does not dominate at the distance of the Stream. Local HVCs with established distance bounds may provide a better calibration of $f_{\text{esc}}$, but significant uncertainties remain as we show. Hα distances may already reveal that some HVCs are dispersed throughout the Galactic halo (§6). In §7, we discuss possible explanations for the Stream emission and propose observational tests.

2. Do ionizing photons escape star forming regions?

This topic remains highly controversial. About the only issue not in dispute is that something is ionizing and heating the gas in the haloes of star-forming galaxies. Enhanced temperatures and high levels of ionization are frequently observed in filaments and in diffuse line emission several kiloparsecs from the galactic plane (Rand 2000). The radiation fields from the cosmic background, galaxy group or the hot galactic halo are much too weak (Maloney 1993; Maloney & Bland-Hawthorn 1999, hereafter MB).

We know that a sizeable fraction of UV photons do not escape star forming regions. Bronfman et al. (2000), after selecting embedded massive stars from their distinctive FIR colours, show that about $5.6 \times 10^{52}$ ionizing photons per second are required to generate the total FIR luminosity. This is about $20-25\%$ of the expected photon rate from the Galaxy (B99a; McKee & Williams 1997). Of the remaining photons, a large fraction is presumably absorbed within more diaphanous star-forming complexes or within the diffuse medium.

The Reynolds layer in the Galaxy, and its counterpart in external galaxies, appears to require at least 15$\%$ of the O (and B1) star ionizing flux, and close to 100$\%$ of the supernova kinetic energy (Reynolds 1984; Domgørgen & Mathis 1994; Hoopes & Walterbos 2000). Since we know that UV does manage to escape some H II regions (Rubin et al. 1991; Oey & Kennicutt 1997), the jury has tended to side with hot, young stars while accepting that it is unclear how the UV manages to get out.

An argument used against UV escaping the Galaxy altogether (M. Walker, private communication) is that the H i halo gas extends vertically to 4 kpc in NGC 891 (Swaters et al. 1997). But the diffuse plasma shows high ionization out to 5 kpc (Rand 1997). Swaters’ H i data is at relatively low resolution (15′′) and is integrated through the galaxy over a very long baseline (∼20 kpc). The high resolution dust pictures of Howk & Savage (2000) reveal that the halo gas is very filamentary. For the Galaxy, Koo, Heiles & Reach (1992) have found related H i structures extending from the plane.

Some of the best evidence that UV must escape the Galaxy comes from the measured electron density profile from halo pulsars. Manchester & Taylor (2000; see also Nordgren, Cordes & Terzian 1992) have modelled this with a scale height of 800 pc which exceeds or is comparable to the scale height of the diffuse H i (warm neutral medium; Lockman 1984). Without fine-tuning, it is unlikely that the Reynolds layer represents a radiation-bounded medium.

1O star UV luminosities are correct to within 50$\%$, but B stars are much more uncertain and could contribute a useful fraction of ionizing photons at high latitudes.
within a co-extensive H I envelope. We know that the radiation field must be soft from the weakness of HeIλ5876 and non-detection of HeIIλ4686 (Reynolds & Tufte 1995). Furthermore, the observed weakness of [OI]λ6300/Hα indicates two things: (i) the ionization fraction must be high (Reynolds 1989), (ii) all of the UV photons produced in the disk cannot be absorbed in radiation-bounded H II regions (Dongörgen & Mathis 1994).

The escape problem may be overstated in the context of the most powerful star-forming complexes which are presumably responsible for most of the UV production. We now know that the spirals with extended H+ haloes are those with high star formation rates (Rand 1996; Lehnert & Heckman 1996). It may be that the processes which propel gas into the halo are the same processes which help UV get out. The observed filaments along the minor axis of superwind galaxies show a clear signature of OB star photoionization and gradual dilution with altitude (q.v. Greve et al. 2000). On smaller scales, this may be what is happening around individual star-forming complexes which are expected to produce a complex network of superbubbles or chimneys bursting out of the stratified medium (Rosen, Bregman & Kelson 1996; Mac Low 1998; Shelton 1998). Indeed, Veilleux (2000, this meeting) presented a spectacular HST Hα image of NGC 3079 which supports this: hundreds of vertical filaments are seen emanating from star-forming complexes across the entire optical disk.

3. Estimates of $f_{esc}$

From observations of four UV-bright starburst galaxies with the Hopkins Ultraviolet Telescope, Leitherer et al. (1995) determined upper limits to $f_{esc}$ of 1, 2, 5 and 15%, (for Mrk 496, IRAS 08339+6517, Mrk 1267 and Mrk 66, respectively) and concluded that the escaping fraction must be small. Their analysis did not take into account the absorption of ionizing radiation by the Galaxy, however, and as shown by Hurwitz, Jelinsky & Dixon (1997), this correction raises the above limits to 3, 5, 11, and 57%, so that they no longer provide reliable 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.) More recently, Steidel, Pettini & Adelberger (2000) have determined that a significant fraction of ionizing photons ($f_{esc} \gtrsim 7\%$) escape Lyman break galaxies at $z \sim 3.4$.

B99a pinned their hopes on the Magellanic Stream (Fig. [1]), which passes over the South Galactic Pole, for an improved estimate of $f_{esc}$ ($\approx 6\%$) but this model underestimates the required flux by at least a factor of 5. (Their escape value $\hat{f}_{esc}$ is defined orthogonally to the disk plane; the solid-angle averaged value is $f_{esc} \approx 1-2\%$.) It now seems that the Stream Hα cannot arise from the disk UV field (although see §7) not least because Weiner et al. (2000) find that certain Stream pointings are much brighter than the values modelled by B99a (see also Putman et al. 2000). However, it turns out that the originally derived $\hat{f}_{esc}$ is within the required range to explain nearby HVCs (§6), assuming they are photoionized by disk stars.

Theoretical models of the transport of ionizing radiation within an idealized Galactic disk suggest that approximately 10% of the ionizing photons produced within the Galaxy escape the disk entirely (Dove, Shull & Ferrara 2000; Fransson & Chevalier 1985; Miller & Cox 1993; Bregman & Harrington 1986; Dongörgen
Figure 1. The LMC, SMC, Magellanic Stream and part of the Leading Arm from the HIPASS H I survey (Putman et al. 2000).
Another theoretical approach which should be considered is a fractal gas distribution superimposed on the McKee-Ostriker 3-phase model of the ISM.

4. The halo UV field: smooth or patchy?

The structure of the UV halo field is particularly important and should help to resolve several key issues. A smooth ionizing halo is more likely to provide a useful distance constraint through the surface Hα emission. In Fig. 2b, we show the predicted halo field for a smooth exponential disk with uniform dust opacity and an escape fraction of $\hat{f}_{\text{esc}} = 6\%$ normal to the disk. (The solid-angle averaged escape fraction in this model is $f_{\text{esc}} \approx 1 - 2\%$.) If the halo field is very patchy, then the Hα distance constraint may be limited to arguing that some objects are within the sphere of influence of the Galaxy (detections) and some are further afield (non-detections).

In external galaxy haloes, Rand (1999; 2000) generally sees smooth rising trends in [SII]/Hα and [NII]/Hα with $|z|$, suggesting a smooth, global ionizing source. But local variations are also seen when comparing parallel slits, and along a given slit on either side of the galaxy plane. Collins & Rand (2001) note that the local variations may be specific to filaments (rather than the diffuse emission) and seem to require an additional source of ionization.

The UV field from massive stars alone is expected to be patchy. In her PhD thesis, Cianci (2001) has compared optical line maps with UV images of spirals observed by the Ultraviolet Imaging Telescope (UIT) aboard the Space Shuttle. In all cases, there is a 90% match or better between UV-identified and Hα -identified H II regions. In other words, the UV images are almost indistinguishable from the Hα maps which often means that clear spiral arms are seen, particularly in late-type spirals. For the Galaxy, the locations of the spiral arms — particularly the direction of the tangent points — are fairly well defined (see Fig. 2a; Taylor & Cordes 1993) and this has important consequences for Hα distance constraints (§6).

The most energetic H II regions in spirals generally appear to be ‘naked’, i.e. dust does not appear to disrupt their morphology. Indeed, in his comments after the talk, R. Allen noted that this has been known a long time. In a series of papers, Rozas, Knapen and Beckman (e.g. Beckman et al. 1999) argue that the H II region Hα luminosity function appears to have a natural break at high luminosity. Their preferred explanation is that UV escapes the most energetic systems.

The UIT images all show evidence of a diffuse inter-arm UV component. But the UIT bands are set at lower energies than Lyman continuum photons and therefore probably include a major contribution from AF stars. In most cases, the UIT images do not rule out the possibility of a more dispersed, low surface brightness disk component, either from runaway OB stars (Lynds 1980; Hoogerwerf et al. 2000) or field O stars (Patel & Wilson 1995; q.v. Massey et al. 1995).

Notably, Slavin, McKee & Hollenbach (2000) have recently proposed that cooling hot gas in old supernova remnants could contribute significantly to the diffuse ionizing field in the disk. This may appear to contradict our earlier statement (§2) that halo coronal gas provides only a weak EUV field. But the
coronal halo parameters (B99a) produce a field that is harder than Slavin’s field and is therefore much less efficient in ionizing hydrogen. Slavin et al. find that roughly a third of the original supernova explosion energy can re-emerge at the remnant stage as a diffuse EUV field. But we note that this phase may in fact help the O star flux reach the outer halo, and may even help to smooth out the disk UV field.

5. A circular problem

The Hα distance constraint (Bland-Hawthorn et al. 1998, hereafter B98) was originally formulated to give some indication of whether HVCs are a relatively local phenomenon or distributed on scales of tens of kiloparsecs. But it relies on our knowing the mean intensity and distribution of the halo ionizing field, which in turn relies on Hα from an H i screen of known distance, covering fraction, topology and orientation to our line of sight (Bland-Hawthorn & Maloney 1999b, hereafter B99b). We originally considered the Magellanic Stream which goes directly over the South Galactic Pole and has been detected in Hα (Weiner & Williams 1996), but certain parts of the Stream now appear to be too bright to be explained by the disk UV field (§7).

D.W. Sciama (1997, personal communication; see also Bregman 1999) proposed using high-velocity clouds to estimate $f_{\text{esc}}$, but at that time, there were few with useful distance constraints. The situation really has not improved much over the last three years. From the clouds which have been detected, we derive $\hat{f}_{\text{esc}} \approx 3 - 12\%$ (solid-angle averaged, $f_{\text{esc}} \approx 1 - 4\%$) by comparing these data to the predicted emission measures from a smooth exponential disk model and a spiral arm model (Bland-Hawthorn & Maloney 2001, in prep.).

There are several concerns with our application to HVCs. Note that most clouds are located within 10 kpc of the Sun’s position. For a realistic model,
we would at least expect that HVCs ‘outside’ are generally fainter than HVCs ‘within’ the Solar Circle, with or without the presence of spiral arms (see Fig. 3). The influence of the Solar Circle is barely evident from so few clouds.

Another issue is that at least two HVCs (B98; Putman et al. 2000) have elevated [NII]/Hα emission. Here, we are forced to assume that the [NII] emission indicates simply an enhanced electron temperature (Reynolds, Haffner & Tuft 1999), rather than the presence of a more pernicious source (e.g. shock heating). There is a variety of ways to produce this effect, e.g. photoelectric heating (Wolfire et al. 1995). This may not be a major concern, since after all we know that high latitude gas in spirals shows enhanced low-ionization emission (Haffner, Reynolds & Tuft 1999; Veilleux et al. 1995). In essence, we can use the elevated [NII]/Hα to argue that some HVCs are more than several kiloparsecs from the plane, and comprise part of the extended ionized atmosphere seen in external galaxies.

6. Where are high velocity clouds?

Wakker & van Woerden (1997) have expounded on the complex history associated with high-velocity clouds. It is difficult to assign their true importance to astrophysics without a mean distance to the population. For example, a mean distance of (5, 50, 500) kiloparsecs leads to a total H1 mass of roughly (10^7, 10^9, 10^{11}) M⊙.

Bland-Hawthorn & Maloney (2001) show that the Hα emission measures of HVCs [E_m/(obs)] are broadly consistent with the BM99 model [E_m(model)]. But the model does not explain the Magellanic Stream detections, as we discuss in the next section. Our analysis includes all HVCs with at least one known distance bound, as summarized by Wakker (2000), with the exception of 5 HVCs which are within 10° of the Galactic plane. The emission measures are from the Las Campanas (Weiner et al. 2000), WHAM (Tuft et al. 1998; Haffner 2000) and TAURUS surveys (Putman et al. 2000). To within a factor of a few, an escape fraction of f esc = 6% is consistent with the observed emission measures. The predicted emission measures arise from calculating the expected flux over different cloud facets which see the disk, for a range of distances within the allowed constraints. (For clouds with upper distance bounds, we have adopted a lower bound of 0.5 kpc.) We emphasize that the predictions are at best broadly descriptive since the Galaxy is modelled with a smooth exponential disk. There must be large local variations in Hα due to line-of-sight effects, limb brightening, unrelated structures at low latitude, and so on. For our crude estimate of f esc to be valid, it is crucial that future Hα surveys of nearby HVCs show the influence of the Solar Circle (§5). This is a necessary but not a sufficient condition. We would also expect to see the influence of the spiral arms along their tangent points in longitude (cf. Fig. 2). If the Solar Circle is evident in the data, but not the spiral arms, this might argue that f esc is much less than 6%, and that something like the EUV field of Slavin et al. (2000) dominates the ionization.

If the Hα normalization to local HVCs is valid, this may indicate that some HVCs which are faint or undetected in Hα (Weiner et al. 2000; Putman et al. 2000), particularly those at high latitude, are probably dispersed throughout the extended halo on scales of 50 kpc or more.
7. The Magellanic Stream.

**Distance problem.** Do we really know the distance and overall distribution of Stream H\textsc{i} in the absence of stellar probes along or close to the Stream? Who is to say that, seen from a vantage point 3 Mpc distant, the Galaxy’s environs do not resemble something like the complex H\textsc{i} network in the M81/M82 group (Yun, Ho & Lo 1994).

Our ‘intuition’ is strongly guided by a slew of dynamical models, which show tidal tails extending from either the SMC\textsuperscript{2} or from the LMC-SMC Lagrangian point (Gardiner & Noguchi 1996; Li 1999). In other words, we are strongly dependent on intuition guided by numerical models (Gibson et al. 2000). However, few of these models properly treat the gas or otherwise we would understand why the Magellanic Stream appears to have no stellar counterpart (de Vaucouleurs 1954; Recillas-Cruz 1982; Tanaka & Hamajima 1982; Brück & Hawkins 1983; Westerlund 1990), although it is possible to contrive models which separate gas and stars along tidal arms (Yoshizawa & Noguchi 1999). What we can say is that the LMC-SMC binary interaction within the extended dark halo of the Galaxy is highly complex and we are far from a detailed understanding of it.

Better distance estimates to different parts of the Stream may come from halo RR Lyrae or blue horizontal branch stars using the foreground-background technique to establish distance brackets. These can be easily picked out to at least 100 kpc with high quality photometry.

In Fig. 3, we show three plausible configurations for the Stream, each of which illustrates a point. Fig. 3a presents a Stream that is highly dispersed in a plane where the inner edge of the Stream is much closer (say 20 kpc) than the assumed mean distance of 55 kpc\textsuperscript{3}. This configuration may help to explain two observations: (i) the exceptionally strong H\textalpha emission along certain sight lines (§7), and (ii) the appearance of H\textsc{i} lanes in Fig. 1 arising from tangent points due to slight undulations or structure within the Stream. The advantages of the other configurations are discussed below.

**Ionization problem.** A nagging problem with H\textalpha distances is the failure to explain the brightest H\textalpha detections along the Stream. For example, Weiner et al. (2000) have detected emission measures at MS II as high as 400 mR, compared with 25–40 mR from the B99\textalpha model at that same position. Even the most contrived models may fail to patch up this discrepancy since the cloud would need to be 3–4 times closer (in the absence of limb brightening).

Since the stellar searches to date have been limited in scope, young massive stars may have been missed along the Stream and these could explain some of the H\textalpha emission. A case in point is the Shapley stellar wing in the Magellanic Bridge (Courtes et al. 1995, Fig. 1) which has been shown to include stars with ages less than 16 Myr (q.v. Demers & Battinelli 1998; Rolleston et al. 1999). This region is very bright in H\textalpha (~3R; Marcelin, Boulesteix & Georgelin 1985; Veilleux et al. 2000).

\textsuperscript{2}The canonical distances for the LMC and SMC are 50 and 60 kpc respectively although Udalski et al. (1998) find that both are probably 15% closer.

\textsuperscript{3}Note that models involving viscosity predict that the ‘tip’ of the Stream at MS VI can be at least as close as 20 kpc (Moore & Davis 1994).
Figure 3. Three possible configurations for the Magellanic Stream in order to explain the observed H I/Hα connection: (a) dispersed along the line of sight, (b) braided, (c) crossed.
A few of the H i clouds in the Stream appear to have head-tail morphologies. Originally, Weiner & Williams (1996) suggested possible Hα limb brightening ahead of the Stream clouds giving support for shocks, but new data makes this proposition less likely (Weiner et al. 2000). In fact, almost any overdensity contrast with the surrounding gas will confine the cloud, i.e. a far wider parameter space than the narrow range of parameters which produces optical shock emission (Murali 2000).

The radiative regions in shocks are in pressure equilibrium with the external gas (Sutherland & Dopita 1993) such that \( n_A v_{LMC}^2 \approx n_S v_S^2 \) where \( n_A \) is the ambient density, \( v_{LMC} \) 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 (B99a); 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 Stream emission measures 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 \( v_{LMC} = 213 \pm 49 \) 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 not enough to ionize hydrogen.

So what about self-interaction? Cloud collisions of 20 km s\(^{-1}\) or more produce H\(\alpha\) through collisional excitation (with partially suppressed H\(\beta\) emission relative to H\(\alpha\)). If we could arrange to bang together H i clouds at 80 km s\(^{-1}\) or more, collisional ionization makes life more interesting, particularly if we allow for moderate levels of pre-ionization by the Galactic disk. Fig. 3b and 3c show two interesting configurations. Fig. 3b is a braided trailing Stream arising from the binary orbit of the LMC–SMC system. Fig. 3c has the Stream colliding with either its own tail (since the LMC-SMC system must precess within the extended halo) or with the H i stream of some other infall object (cf. Putman et al. 2000). This picture is appealing because CDM advocates propose that the Galactic halo is made up of hundreds or even thousands of debris streams from accretion of small stellar systems (Wyse 1999), some of which were presumably gas rich.

What are the likely shock signatures? The post-shock velocity should lead to a detectable offset from the H i cloud. If the MS clouds really are limb-brightened at the head of the shock, then this offset might not be detectable since the clouds are overhead, but the bowshock curvature should produce a detectable asymmetric wing in the line profile (20 km s\(^{-1}\) resolution or better).

If the shock velocity is less than 100 km s\(^{-1}\), then ionization is produced in the shock itself, and there is a large collisional contribution to the Balmer lines and the 2-photon continuum (Sutherland & Dopita 1993; Shull & McKee 1979). Every ionized atom will make one recombination going through the shock, and this provides the H\(\alpha\) flux. (At somewhat higher velocity, collisional excitations of the neutrals become important.)

In order of increasing shock velocity (20 \(\rightarrow\) 100 km s\(^{-1}\)), the progression in well known optical diagnostics is:

- large Balmer decrement, strong [O I];
- large Balmer decrement, strong [O I] and [S II];
- normal Balmer decrement, [N II] and [O II] becoming strong;
normal Balmer decrement, [OIII] appears.

When interpreting the conventional shock diagnostics, one must keep in mind that the gas-phase $\alpha$-elements (as judged from SMC) are $4-5$ times lower than Solar abundance, and secondary products (e.g. N) are suppressed compared to the $\alpha$-elements by a similar factor (Gibson et al. 2000). This calls for long exposures on the low ionization lines to be sure of reaching the necessary sensitivity.

We note that partial pre-ionization by the Galactic disk can assist the shock process since it lowers the required shock velocity to achieve a given post shock temperature (cf. Shull & McKee 1979). Could differential cloud-cloud motions along the Stream be sufficient to generate local Hα enhancements? The configuration in Fig. 3b might be able to produce (adiabatic) shock velocities of 20 km s$^{-1}$. However, within the errors, the H I and Hα projected velocities appear to be the same.

In fast shocks, the shock-generated UV spectrum can ionize the gas ahead of the shock. A shock velocity of 100 km s$^{-1}$ is needed to produce nearly complete pre-ionization from the shock itself. At even higher shock velocities ($>175$ km s$^{-1}$), an equilibrium H II region is produced ahead of the shock. Here, we would need a configuration like Fig. 3c where H I debris trails are on very different trajectories.

**Simple test.** The Hα distribution along the Stream could provide the fundamental clue. If Hα peaks at the poles, this indicates knowledge of the Galaxy either through the presence of disk photoionization (B99a), shock pre-ionization, a Galactic wind/fountain, or whatever. If Hα is bright at large angles from the poles (e.g. MS V–VI), this argues for something like Fig. 3b, and against a dominant Galactic influence, unless the tip happens to be much closer to the disk. Any strong Hα asymmetry in Galactic coordinates argues for shock interactions similar to Fig. 3c.

8. **Future studies**

We began this overview by acknowledging that the IGM has become one of the main frontiers of modern astrophysics, largely driven by exquisite absorption-line data from quasar spectra. This is a difficult topic which will require careful study over many years. Progress will come from tackling the problem from many directions, starting with our own backyard, i.e. the Galactic halo and the Local Group medium.

A full understanding of the halo and the role of HVCs will be slow in coming since the physical processes are undoubtedly complicated (e.g. Wolfire et al. 1995). Hot gas has been detected along many sight lines through the halo (q.v. Sembach et al. 1998). This presumably arises from cooling hot gas becoming opaque to its own radiation field, thereby indicating a complex multi-phase halo. A rather exotic possibility is halo material interacting with the IGM as the Galaxy sweeps through the Local Group. Important clues will come from observing external galaxies much like our own. For example, in NGC 5755, while there is evidence for a large-scale, smoothly distributed source of halo ionization, the amplitude and variation in [OIII]/[NII] clearly indicates secondary sources (Collins & Rand 2001).

We can anticipate help from unexpected sources. The Square Kilometre Array should detect pulsars in Local Group galaxies and thus provide plasma
densities within the warm intergalactic medium (MB). The Sloan Digital Sky Survey should be able to identify stellar probes in the outer halo on 100 kpc scales, and provide a distance ladder of stellar probes at intermediate distances. Future space astrometry missions may reveal debris trails from hundreds of disrupting stellar satellites (‘spaghetti halo’), and we can foresee that the orbital parameters of these may account for some of the HVC population.

We suspect that a reliable determination of $f_{esc}$ for the Galaxy is a necessary first step in understanding the halo ISM. An interesting side product of $f_{esc}$ (assuming greater than 1% or so) is a crude distance constraint to H I clouds through the Hα emission, even if only to clearly indicate which clouds are or are not within the Galactic sphere of influence. Fully convincing models of the Stream interaction may require essentially complete Hα maps along its length at similar resolution to the HIPASS H I maps. But future absorption line studies using background probes will be crucial for revealing how much of the story is taking place at low electron and neutral columns ($< 10^{16}$ particles cm$^{-2}$), i.e. whether the Stream is largely confined to the famous H I arc, or whether it extends over a much greater solid angle (cf. Gibson et al. 2000).

Acknowledgments. We are indebted to Brad Gibson for his insights and help with all aspects of this work. JBH thanks Chris McKee for his combat and continued inspiration in this field. We benefitted from dialogues with Phil Maloney, Sylvain Veilleux, Ben Weiner, Rich Rand, Mark Giroux and Jonathan Slavin.

References

Allen, R. et al. 1997, ApJ, 487, 171
Beckman, J. et al. 1999, AJ, 119, 2728
Bland-Hawthorn, J. & Maloney, P.R. 1999, ApJ, 510, L33 (B99a)
Bland-Hawthorn, J. & Maloney, P.R. 1999, ASP166 Stromlo Workshop on HVCs B.K. Gibson & M.E. Putman212 (B99b)
Bland-Hawthorn, J. et al. 1998, MNRAS, 299, 611 (B98)
Bregman, J.N. & Harrington, 1986, ApJ, 309, 833
Bregman, J.N. 1999, ASP166 Stromlo Workshop on HVCs B.K. Gibson & M.E. Putman88
Bronfman, L. et al. 2000 [astro-ph/0006104]
Brück, M.T. & Hawkins, M.R.S. 1983, A&A, 124, 216
Cianci, S. 2001, PhD, Univ. of Sydney
Collins, J. & Rand, R. 2001, ApJ, in press
Courtes, G. et al. 1995, A&A, 297, 338
Demers, S. & Battinelli, P. 1998, AJ, 115, 154
Domgörgen, H. & Mathis, J.S., 1994, ApJ, 428, 647
Dove, J.B., Shull, J.M. & Ferrara, A. 2000, ApJ, 531, 846
Fransson, C. & Chevalier, R.A. 1985, ApJ, 296, 35
Gardiner, L.T. & Noguchi, M. 1996, MNRAS, 278, 191
Gibson, B.K. et al. 2000, AJ, in press [astro-ph/0007078]
Greve, A., Neininger, N., Tarchi, A. & Sievers, A. 2000 [astro-ph/0101116]
Haffner, L.M., Reynolds, R.J. & Tufte, S.L. 1999, ApJ, 523, 223
Henry, R.C. 1991, ARAA, 29, 89
Hoopes, C.G. & Walterbos, R.A.M. 2000 (astro-ph/0007309)
Howk, J.C. & Savage, B.D. 2000, AJ, 119, 644
Hoogerwerf, R., de Bruijne, J.H.J. & de Zeeuw, P.T. 2000 (astro-ph/0010057)
Hurwitz, M., Jelinsky, P., Dixon, W. 1997, ApJ, 481, L31
Koo, B., Heiles, C. & Reach, W.T. 1992, ApJ, 390, 108
Kulkarni, V.P. & Fall, S.M. 1993, ApJ, 413, L63
Lehnert, M. & Heckman, T.M. 1996, ApJ, 462, 651
Leitherer, C. et al. 1995, ApJ, 454, L19
Li, P.S. 1999, PhD, University of Wyoming
Lin, D.N.C., Jones, B.F. & Klemola, A.R. 1995, ApJ, 439, 652
Lockman, F.J. 1984, ApJ, 283, 90
Lynds, B.T. 1980, AJ, 85, 1046
McKee, C.F. & Williams, J.P., 1997, ApJ, 476, 144
Mac Low, M.M. 1999, ASP168 New Perspectives on the ISM A. R. Taylor, T. L. Landecker, & G. Joncas303
Maloney, P.R. 1993, ApJ, 414, 41
Maloney, P.R. & Bland-Hawthorn, J. 1999, ApJ, 522, L81 (MB)
Manchester, R.N. & Taylor, J.H. 2001, Pulsars (W.H. Freeman: San Francisco), in prep.
Marcelin, M., Boulesteix, J. & Georgelin, Y.P. 1985, Nat, 316, 705
Massey, P. et al. 1995, ApJ, 438, 188
Miller, W.W. & Cox, D.P. 1993, ApJ, 417, 579
Moore, B. & Davis, M. 1994, MNRAS, 270, 209
Murali, C. 2000, ApJ, 529, L81
Nordgren, T.E., Cordes, J.M. & Terzian, Y. 1992, AJ, 104, 1465
Oey, M.S. & Kennicutt, R.C. 1997, MNRAS, 291, 827
Patel, K. & Wilson, C.D. 1995, ApJ, 451, 607
Putman, M.E. et al. 1998, Nat, 394, 752
Putman, M.E. et al. 2000, in preparation
Rand, R. 1996, ApJ, 462, 712
Rand, R. 1997, ApJ, 474, 129
Rand, R. 1998, ApJ, 501, 137
Rand, R. 2000, ApJ, 537, L13
Reynolds, R.J. 1984, ApJ, 282, 191
Reynolds, R.J. 1989, ApJ, 345, 811
Reynolds, R.J. & Tuft, S.L. 1995, ApJ, 439, L17
Reynolds, R.J., Haffner, L.M. & Tuft, S.L. 1995, ApJ 525, L21
Rolleston, W.R.J. et al. 1999, A&A, 348, 728
Rosen, A., Bregman, J.N. & Kelson, D.D. 1996, ApJ, 470, 839
Rubin, R. et al. 1991, ApJ, 374, 364
Shelton, R.L. 1998, 504, 785
Shull, J.M. & McKee, C.F. 1979, ApJ, 227, 131
Slavin, J.D., McKee, C.F. & Hollenbach, D.J. 2000, ApJ, 541, 218
Steidel, C.C., Pettini, M. & Adelberger, K.L. 2000 (astro-ph/0008283)
Sutherland, R. & Dopita, M.A. 1993, ApJS, 88, 253
Swaters, R.A., Sancisi, R. & van der Hulst, J.M. 1997, 491, 140
DISCUSSION:

Ron Allen: It is intriguing how often the most energetic H II regions generally seem to be ‘naked’ (e.g. M81; Allen et al. 1997). But we’ve known this since the old WSRT maps of thermal emission in nearby galaxies showed no bright discrete sources which were not also visible as H II regions in H α.

Todd Tripp: Nice evidence for UV flux escaping from galaxies (at high redshift) has been provided by the He+ Gunn-Peterson observations presented by Alain Smette. He showed regions in the spectra of high redshift QSOs in which the H I opacity is extremely low and yet the HeII opacity is extremely high. This suggests that these regions are ionized by very soft sources, i.e. not quasars. UV flux escaping from, say, a star-forming galaxy provides an appealing explanation.

Joss Bland-Hawthorn: There is some support for Smette’s argument from recent observations of Lyman-break galaxies: these appear to be a significant source of UV flux (see Steidel et al. 2000).

Sergei Marchenko: If most UV photons escape from H II regions through chimneys, then the external UV field should be very patchy which makes the Hα measurements as a distance indicator for HVCs questionable. Is this correct?

Joss Bland-Hawthorn: That depends on the opening angle of the chimneys. If they really are vertical tubes, then only a few HVCs are expected to light up, i.e. those caught in the searchlight beams. But if the chimneys have reflecting walls (like skylights commonly used in Australian households) or are slightly conic, then the halo field will become uniform at some distance above the plane (related to the mean spacing between the UV sources). Observations already show large opening angles above the most powerful star-forming regions (Veilleux, this meeting), but therein lies the rub. These complexes are often widely spaced over the disk.