Galaxies

1 The ISM of the Milky Way

1.1 Hot Gas

Highly ionized species trace warm/hot gas which may be heated either by photo-ionization or collisions. Most commonly we observe Li-like species such as C IV, O VI and N V with resonance transitions $1s^2\ 2s\ ^2S_{1/2} \rightarrow 1s^2\ 2p\ ^2P_{1/2,3/2}$ whose IPs range from $\sim 50 - 110$ eV. Assuming collisional ionization equilibrium, for a fixed abundance the observed N(O VI) peaks $T \sim 10^5$ K with NV and CIV at slightly lower temperatures. OVI is particularly useful because a) it is cosmically abundant and b) it is mostly collisionally ionized. The large IP required to ionize OV to OVI is usually not available from stellar photons since most hot stars have a HeII edge at 54.4 eV (4 Rydbergs). CIV can be photo-ionized by these hot stars (CIII IP = 47.9 eV). OVI can be photo-ionized in low density environments (e.g. the IGM) by a hard UV background.

All these high ions are in the UV, so need a space telescope. Early work done by Copernicus in 1970s, most recently FUSE has made a large impact. To work in the far UV need special detectors and coatings, i.e. HST not ideal.

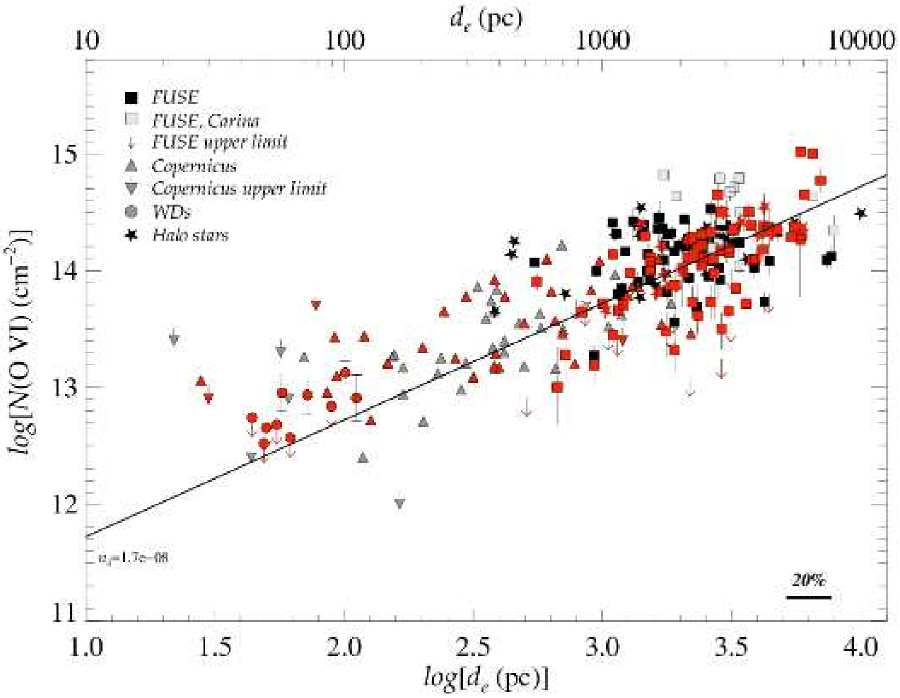

Figure 1: Distrubution of hot gas in the MW disk with distance along disk (Bowen et al 2004).

Some hot gas in the disk is associated with hot bubbles (also trcaed in X-rays) caused by star formation. In the disk, there is a linear relation between log of the distance along the disk and the N(OVI) out to about 10 kpc (Bowen et al 2004, astro-ph/0410008). The process that produces OVI is active from the Galactic centre ($l = 0$) to the ISM between the outer spiral arms ($l = 180$). (Remember, in Galactic coordinates, b is the Galactic latitude, i.e. angle out of the plane, and l is the Galactic longitude, angle around the plane from Sagittarius.) The increase in N(OVI) with d could be explained by intercepting more 'clouds' with longer sightlines, i.e. regular distribution of clouds? Now look at distribution out of the plane i.e. as a function of $| z |$. Now we plot N(OVI) sin$b$ so that we are only looking at the vertical contribution. Again, there is a nice relationship between column density and height, more evidence for 'smooth' distrubution. However, if the clouds had uniform N(OVI) we expect to see smaller dispersion ($sqrtnN$) at higher distances, not the case. So disk ISM must be clumpy and non-uniform i.e. some clouds with higher column densities than others (but still regular).

OVI in the halo also appears to be clumpy and there is a large scatter of N(OVI) in a given direction on the sky (e.g. a given l). There is also a marked difference towards the northern and southern hemispheres. It has been suggested that this could be due to the venting of hot gas from the local bubble out through a chimney.

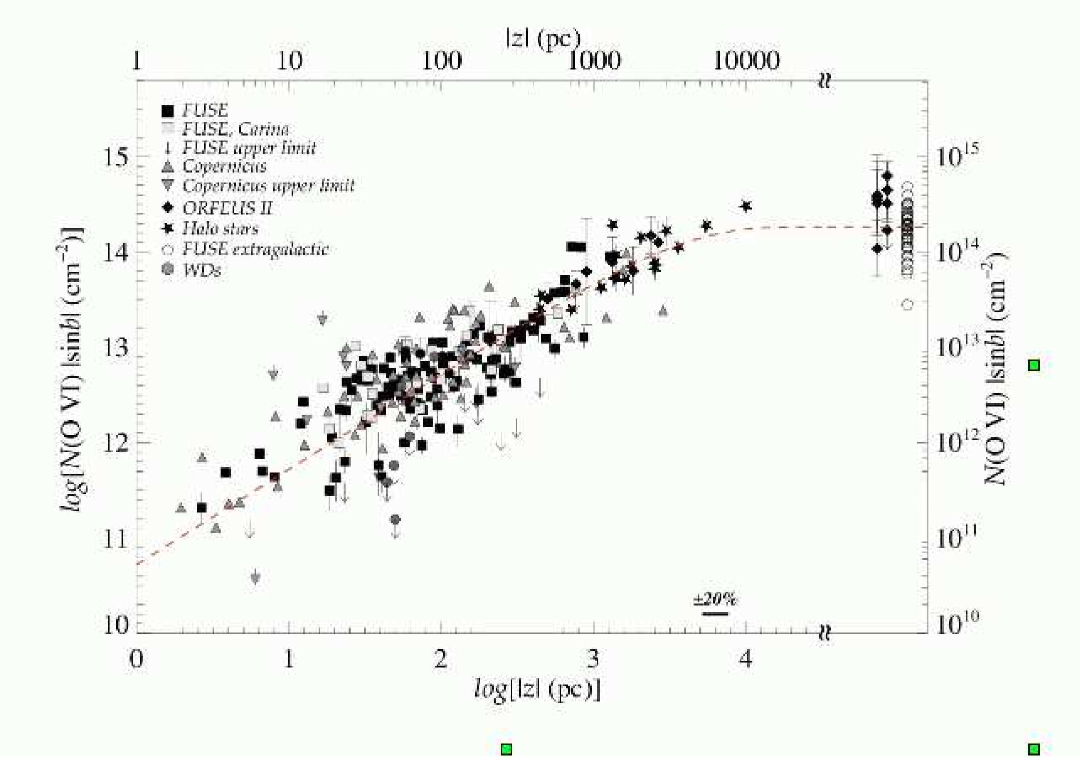

Figure 2: Distrubution of hot gas in the MW disk with height above the plane.

The scale heights (e-folding distances) of the high ions are about 10 times larger than for the neutral HI and about 3 times larger than the warm ionized medium traced by HII regions and AlIII. Among the high ions, those more susceptible to photo-ionization maye have a greater extension than those associated with collisional ionization.

1.2 Cold Gas

Cold gas in the MW seems to be a lot clumpier than warm gas. There is evidence for very small scale variations in the cold gas on scales of 1000s of AU based on

- Observations from pairs of stars closeby on the sky
- Multi-epoch observations of high proper motion stars
- Integral field spectroscopy of globular clusters

This clumpiness is also seen at high redshift in lensed QSOs, where highly ionized gas remains coherent of several kpc, but low ionized gas shows structure on pc scales.

2 High Velocity Clouds

There is an excellent book called 'High Velocity Clouds' editted by van Woerden, Wakker, Schwarz & De Boer published by ASSL in 2004

High and intermediate velocity clouds (HVCs; IVCs) have discrepant velocities compared with the local standard of rest (LSR - point which is instantaneously centred on the Sun and moving in perfectly circular orbit. Note that once defined, the Sun would immediately start to drift from this zero point, but since the cosmic year [$\sim$ 250 million years] is longer than this lecture course, it's usually not a practical problem). The first discovery of HVCs in the early 1960s had some absorption associated with gas $>$ 20 km/s from the LSR. Spitzer famously inferred that if this neutral gas existed outside the disk, it need to be pressure confined, and the confining gas would have to be highly ionized (because it wasn't seen in absorption in the usual low ionization lines). He concluded that a reservoir of 10^6 K gas existed in what he called the Galactic Corona (because such hot gases at that time were always associated with stellar coronae).

Most large scale maps of HVCs have been done with HI 21cm mapping. Some of these structures are huge, e.g. Complex C which covers 2000 square degrees! In the mid 1970s it was discovered that the complex of HVCs near the SGP were part of a chain that connected us to the Magellanic Clouds – the Magellanic Stream. Since radio telescopes have limited 'spectral' (i.e. velocity) coverage, it wasn't until the early 1980s when HVCs were mapped out to $\pm$900 km/s that the maximum LSR velocities appeared to be -450 and $+350$ km/s. There is a marked asymmetry between the north and the south – shreds of the Magellanic Stream or other orbiting objects? For the most part, however, the origins of HVCs was unclear; theories included leftovers from Galactic formation, outer spiral structure, Galactic fountain, gas infall and merging satellites.

Determining distances to the HVCs in order to place them on a Galactic map is hard – only velocity information is easy to obtain. Early on, it was not even clear if this gas was Galactic and it was suggested by some that it was intergalactic primordial gas (since no strong metal lines had yet be observed). Metallicities would also provide a clue to their origin, e.g. disrupted disk gas or intergalactic origin; this had to wait for UV spectroscopy. Lack of either metallicities or distances led to a plethora of different theories for HVC origin (see above). The best way of determining distances is by finding a sample of stars projected onto an HVC and with a range of distances.

Classify the stars (or use parallaxes) to get distances and then obtain high resolution spectroscopy to look for gas absorption due to HVC. Detections and non-detections give upper and lower limits to the distance of the absorber. The distances determined span 1 – 10 kpc, with some clouds associated with the disk, others the halo and some with distances $\sim$ 50 kpc associated with the IGM (e.g. Magellanic Stream).

Determining metallicities has several associated problems. First of all, need to determine an N(HI) and disentangle the HVC from 'normal' Galactic component. This is effectively impossible in Lyα due to the broad line. We can infer an N(HI) from the 21cm observations, but the beam size is often large (10 arcmin) and if the clouds are clumpy we would be averaging over the beam. Unlike the determination of DLA abundances, where we believe the gas is cool and self-shielded, the Galactic halo is diffuse and warm, so the first ionization state is not necessarily dominant. We need to observe several ionizations states and model the contributions. OI is often used because it traces HI through charge exchange. This leads us to another problem - if the gas is diffuse and warm, maybe a significant amount of the hydrogen is HII, rather than HI. Finally, there are the usual caveats about refractory elements and depletion. Typical metallicities range from 0.1 – 0.5 solar

Taken together, what do the metallicities and distances tell us about the origins of HVCs? Whilst distances gave some idea, metallicities are more discriminating. E.g. for a Galactic fountain, metallicities should be like the disk ($\sim$ solar), tidal disruption of the SMC/LMC should give abundances in the range 0.3–0.5 solar and disruption of small dwarfs/primordial infalling gas should have lower metallicities again. Combining distance and metallicity, some HVCs appear to be extragalactic (e.g. Complex C) and some in a fountain (e.g. Complex M). AC clouds maybe debris from the Sag dwarf.

3 Magellanic Clouds

3.1 Magellanic Bridge/Stream

The Magellanic Bridge is a stream of gas connecting the LMC and SMC which is believed to have formed from gas pulled from the SMC during a close encounter $\sim$ 200 Myrs ago. Some stars have been detected in the bridge and have metallicities around 1/13 solar, even more metal poor than the SMC. This seems to indicate that the stars formed in-situ, but chemistry is more easily studied in the gas phase.

3.2 Molecular Hydrogen

Recall from Doug's lecture that the Born-Oppenheimer approximation (see either book by Shu or Rybicki & Lightman) tells us that energies required to excite various states range from a few eV (electronic) to a few tenths of an eV (vibrational) down to $10{-}3$ eV for rotational transitions. I.e. it is easiest to make a molecule rotate! At higher energies have ro-vib spectra and then electronic-ro-vib spectra. H_2 in the ISM is mostly studied with Lyman and Werner bands – ro-vib transitions between the ground and excited electronic states. These occur in the UV and again need a space telescope and can lead to very complicated spectra!

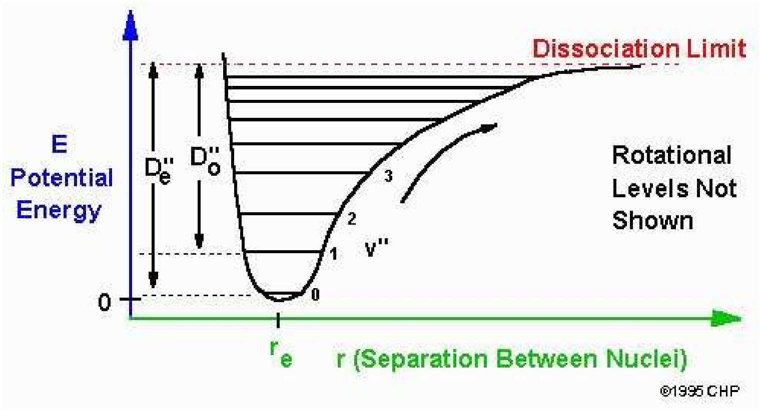

Figure 3: Potential energy between 2 atoms in a molecule as a function of their separation.

Large survey of molecular H done by Tumlinson et al (2002) with FUSE. General (and surprising) result was that while 92% of SMC sightlines had H_2, the percentage was only 52% in the LMC. Perhaps due to patchy structure in LMC which contains many HI superbubbles associated with star formation. SMC is more quiescent.

In the Milky Way, there is a general correlation between colour excess (E(B-V)) and molecular fraction, defined as

$$f(H_2) = \frac{2N(H_2)}{N(HI) + 2N(H_2)} \tag{1}$$

There is a characteristic breakpoint at E(B-V) $\sim$ 0.08 where the molecular fraction seems to suddenly increase. In the MCs, however, there is a large scatter in $f(H_2)$ at a given E(B-V), included fractions as high as 10^{-2} at E(B-V) $\sim$ 0.03.

3.3 Diffuse Interstellar Bands

For the first time, the DIBs are now being studied in the Magellanic Clouds. Detections are still relatively few, but studying correlations in DIBs in external galaxies is an important test of their origins. For example, the family hypothesis in which the correlation of certain DIB EWs is explained by a common origin needs to be tested in different galaxies which have different ISM properties. Another interesting correlation of DIBs in the Galaxy is that some correlate with N(HI). Does this occur in other galaxies? Perhaps, but we probably have to scale the relationship for metallicity as well.

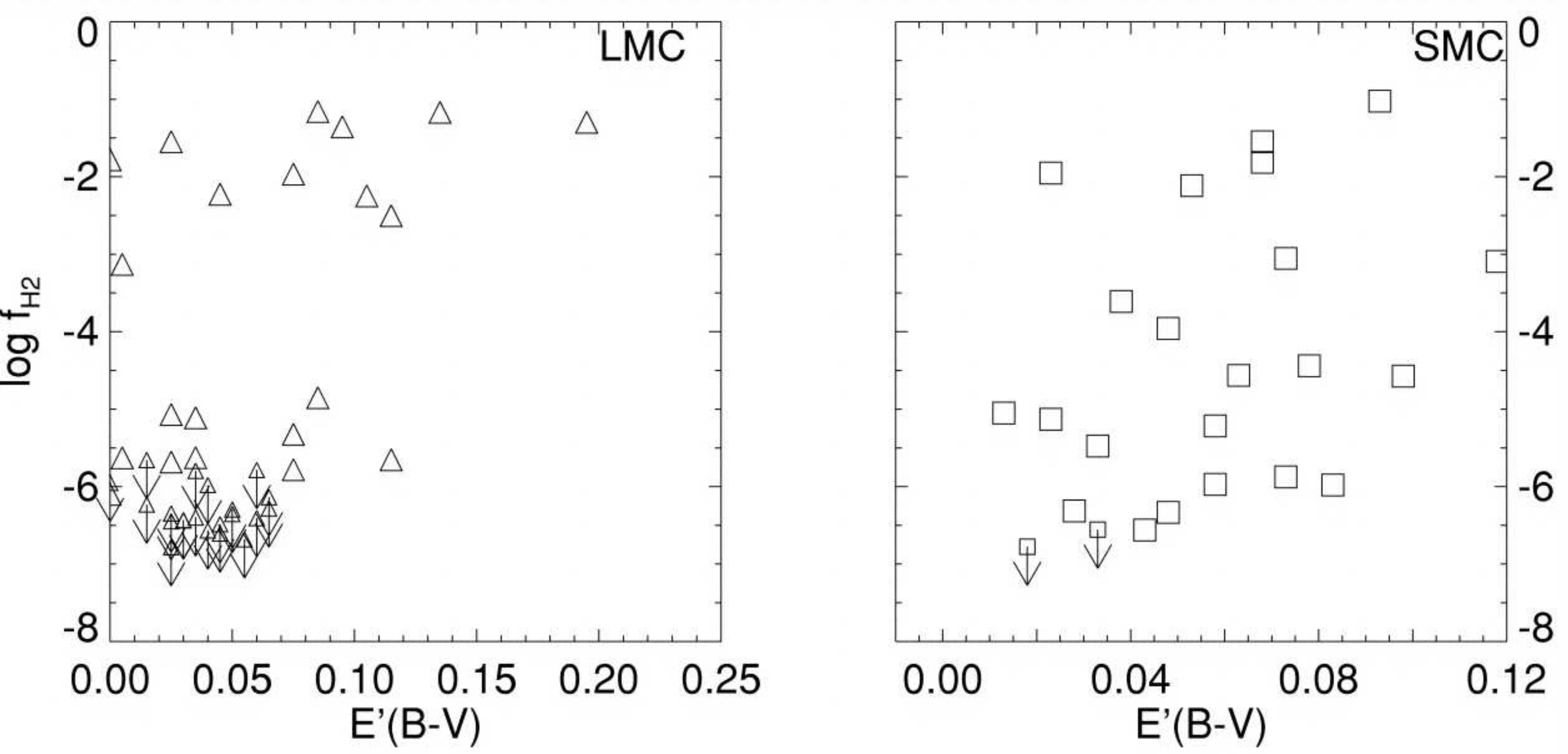

Figure 4: Fraction of molecular hydrogen in the Magellanic Clouds (Tumlinson et al. 2002).

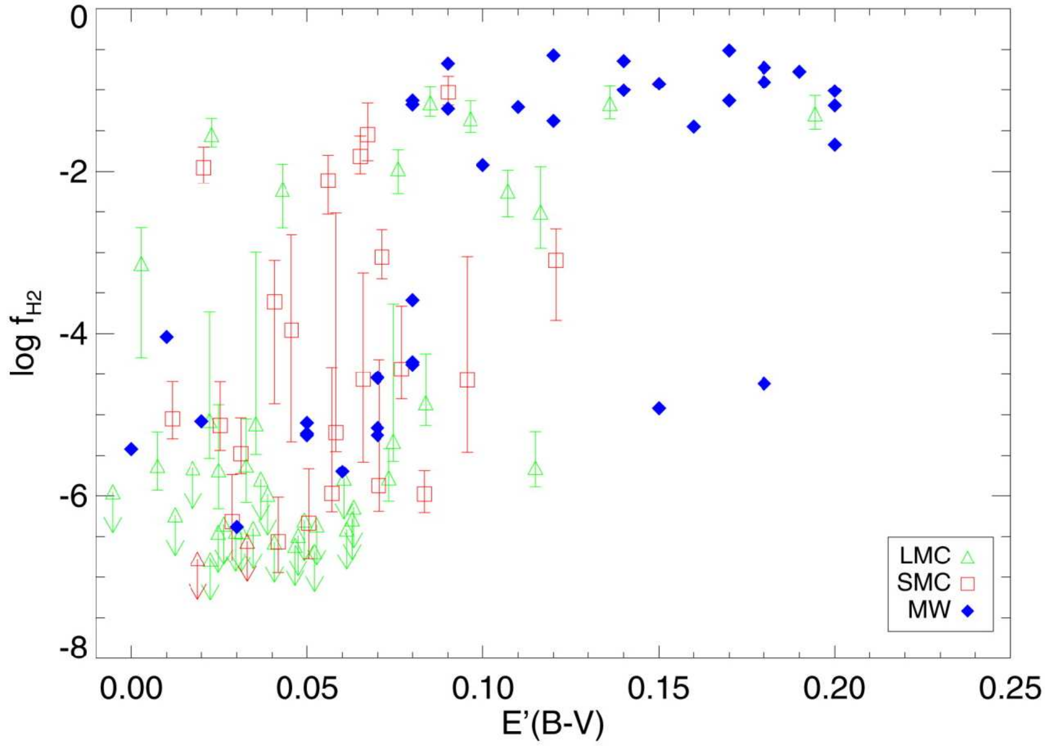

Figure 5: Fraction of molecular hydrogen as a function of E(B-V) in the Magellanic Clouds and Milky Way (Tumlinson et al. 2002).