Part 1. Census

From High Velocity Clouds to Intergalactic HI

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High-Velocity Clouds and the Local Group

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Abstract. I examine some of the evidence relevant to the idea that high-velocity clouds (HVCs) are gas clouds distributed throughout the Local Group, as proposed by Blitz et al. (1999) and Braun & Burton (1999). This model makes several predictions: a) the clouds have low metallicities; b) there should be no detectable Hα emission; c) analogues near other galaxies should exist; and d) many faint HVCs in the region around M 31 can be found. Low metallicities are indeed found in several HVCs, although they are also expected in several other models. Hα emission detected in most HVCs and, when examined more closely, distant (D>200 kpc) HVCs should be almost fully ionized, implying that most HVCs with H I must lie near the Milky Way. No clear extragalactic analogues have been found, even though the current data appear sensitive enough. The final prediction (d) has not yet been tested. On balance there appears to be no strong evidence for neutral gas clouds distributed throughout the Local Group, but there may be many such clouds within 100 or so kpc from the Milky Way (and M 31). On the other hand, some (but not all) of the high-velocity O VI recently discovered may originate in hot gas distributed throughout the Local Group.

1. Introduction

The presence of high- and intermediate velocity clouds (IVCs and HVCs; gas with velocities deviating by more than ~40 km s^{-1} from differential galactic rotation) has been known for four decades (Muller et al. 1963, Blaauw & Tolbert 1966). Some understanding has now been reached about the location and properties of many of these objects. The IVCs appear to have solar metallicity, z-heights of ~1 kpc, and possibly represent the return flow of a Galactic-Fountain type circulation (see Wakker 2001 and references therein). The Magellanic Stream is a tidal stream extracted from the Small (and maybe also the Large) Magellanic Cloud (Gardiner & Noguchi 1996). One HVC (complex A) lies in the upper Galactic Halo (z=4.6–6.8 kpc; van Woerden et al. 1999). For several other HVCs the intensity of the detected Hα emission also suggests similar z-heights (Weiner et al. 2001), though accurate distances remain unknown. HVC complex C clearly consists of gas that has never been part of the Milky Way before – it has low metallicity (~0.1 times solar; Wakker et al. 1999, Richter et al. 2001).

Although much progress has been made in the understanding of the HVCs, many questions remain. In particular, there is no consensus about the suggestion that many of the small HVCs represent the neutral gaseous component of dark matter halos distributed throughout the Local Group (Blitz et al. 1999). I will review this model (Sect. 2) and the evidence for and against it (Sect. 3). In Sects. 4 and 5, I will discuss the discovery of high-velocity O VI absorption and its relevance to the connection between HVCs and the Local Group.

2. H I HVCs and the Local Group

Fairly early in the study of HVCs, it was suggested that they represented protogalaxies with distances on the order of 400 kpc (Verschuur 1969). Based on this suggestion, but using much more data Hulsbosch (1975) calculated the distances implied if the HVCs in his sample were gravitionally bound objects in virial equilibrium:

$$D_{vir} = f \frac{6\alpha\sigma^2}{0.236SG} \text{ kpc,} \tag{1}$$

where G is Newton's constant of gravity, S is the integrated flux in Jy km s^{-1}, 0.236 is a conversion factor to convert flux to mass, σ is the observed velocity dispersion, α is the angular radius of the cloud, and f is the ratio M(H I)/M(total). Hulsbosch (1975) assumed f=1, and thus found that the implied "virial distances" were typically 0.5–10 Mpc. He concluded that it was unlikely that the HVCs were gravitationally bound and distant.

Verschuur's idea was revived by Blitz et al. (1999), who suggested that HVCs represent the neutral baryonic material in a ten times more massive dark matter halo. That is, Blitz et al. (1999) assumed f=0.1. Using the catalogue of Wakker & van Woerden (1991) they derived that the median distance of a virially stable HVC was reduced to ~1 Mpc, and the median implied mass was ~3×10^7 $M_\odot$, with an integrated total mass in the HVCs of 10^{10} $M_\odot$. They combined these numbers with a basic model of the evolution of the Local Group that predicted the present-day locations and velocities of test particles.

Although Blitz et al. (1999) concluded that the predicted and observed distributions were similar, this conclusion has remained controversial. A major contribution of the Blitz et al. (1999) article was their effort to make testable predictions. These included: a) the HVCs should have subsolar metallicities; b) they should have undetectable Hα emission; c) analogues should be seen in other groups and/or near other galaxies; d) with higher sensitivity many faint HVCs should be seen in the region around M 31. In the next section I will review the current status of these tests.

Following Blitz et al. (1999), Braun & Burton (1999) suggested that only the small HVCs (which they termed "compact HVCs" or CHVCs") were distant Local Group objects. They followed this up by several studies, culminating in the series of papers by de Heij et al. (2002a,b,c). In the final version of their model, there were originally some 6000 CHVCs, but most are unstable against disruption by tides or ram pressure. About 1000 survive, but most are too faint to be detected, or have the wrong velocity to be considered an HVC, leaving just ~150 CHVCs at present. Most lie within 300 kpc of either M 31 or the Milky Way. The total H I mass in these clouds is about 10^9 $M_\odot$, while the most massive CHVC has M~10^7 $M_\odot$. Thus, in this model, the CHVCs are about 10 times less massive and 5 times closer than in the Blitz et al. (1999) model.

3. Observational tests

3.1. Metallicities

Local Group HVCs should have subsolar metallicities. Reliable values are known for just two HVCs – complex C and the Magellanic Stream. Fox et al. (2004) summarize the determinations of S/H and O/H in complex C made by Wakker et al. (1999), Gibson et al. (2001), Richter et al. (2001), Collins et al. (2003) and Tripp et al. (2003), bringing them on the same solar abundances scale. (O/H) is 0.14–0.19 times solar, while (S II/H I) varies from 0.09 to 0.46 times solar, with a strong dependence on N(H I) that is clearly due to varying ionization. For the Magellanic Stream Lu et al. (1998) and Gibson et al. (2000) find (S II/H I)= 0.25–0.30 times solar, equal to the value expected for Magellanic gas.

A preliminary analysis of new data from the Far Ultraviolet Spectroscopic Explorer (FUSE) shows that HVC complex A (l~150°, b~35°, v~−150 km s^{-1}) probably has Z~0.1 solar, complex WB (l~240°, b~20°, v~+100 km s^{-1}) has Z~1 solar, complex WD (l~280°, b~+25°, v~+100 km s^{-1}) has Z~0.1 solar, and cloud WW84 (l=125°, b=+42°, v=−205 km s^{-1}) has Z~0.05 solar.

Clearly, some of the HVCs have strongly subsolar metallicities, showing that they are not Galactic clouds. For complex C we also know that the (N/O) ratio is ten times lower than that in the nearby ISM, and that it has relatively high D/H (Sembach et al. 2004). In the Local Group model, nearby low-metallicity HVCs like complex A and C are the gaseous component of a small halo dark-matter halo that has come close to the Milky Way. However, although low metallicities are expected in the Local Group model, it is not sufficient evidence. Complex C (and other HVCs) could be the remnant of a tidally stripped dwarf galaxy, whose stars are no longer recognizable. Or they could be condensations in a hot (T>10^6 K) extended (R>50 kpc), tenuous (n<10^{-4} cm^{-3}) gaseous Galactic corona.

3.2. Hα observations

Distant HVCs will only be ionized by the extra-galactic radiation field, which is insufficient to produce observable Hα emission. However, Hα emission is detected from many HVCs: Weiner & Williams (1996; the Magellanic Stream), Tufte et al. (1998; complexes A, C and M), Bland-Hawthorn et al. (1998; complex GP), Tufte et al. (2002; four CHVCs), Weiner (2003; complexes L, AC, GCN). Typical intensities lie in the range 0.1–0.3 Rayleigh, with a few limits <0.1 Rayleigh. The results of these now multitudinous detections of Hα emission from HVCs imply that most of them must lie no more than several tens of kpc from the Milky Way. However, there are still many candidate Local Group HVCs whose Hα emission has not yet been observed, so the case is not closed.

Maloney & Putman (2003) looked at this problem from the theoretical side. For CHVCs at distances of ~1 Mpc, the implied H I volume densities are ~3×10^{-4} cm^{-3}. With N(H I) a few 10^{19} cm^{-3} such clouds will be almost fully ionized by the extragalactic ionizing radiation field (5% neutral fraction). If the CHVCs also have a dark matter to baryon ratio of 10, the observed amounts of H I then imply that CHVCs should dominate the dynamics of the Local Group, and would have line widths much larger than is observed. If the CHVCs lie in the Galactic halo (D<200 kpc) their properties give consistent results.

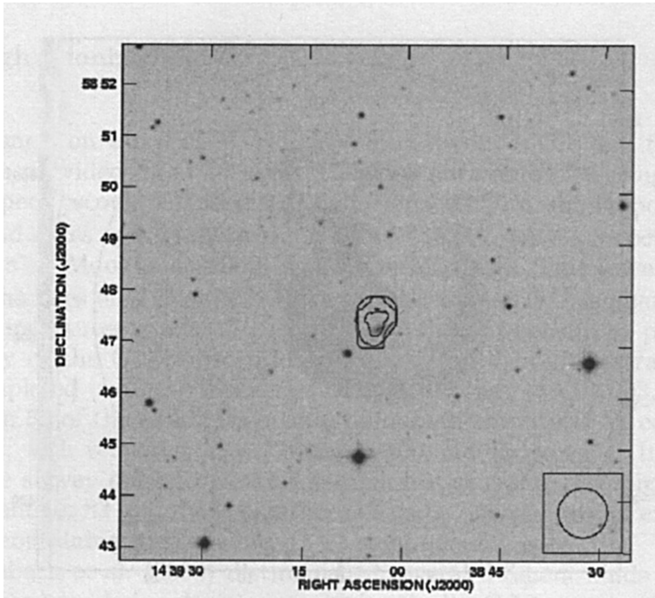

Figure 1. H I column density overlaid on the blue DSS-2 image of PWWF J1439+5847. H I contours are at 0.5, 1, 2, 3×10^{19} cm^{-2}.

3.3. HVCs near other galaxies and galaxy groups

Blitz et al. (1999) argued that searches for HVC analogues near other galaxies and in other galaxy groups were still rather limited and not quite sensitive enough. De Heij et al. (2002c) make the specific prediction that there are 95 CHVCs with mass larger than 3×10^6 M$_\odot$, and 45 with mass $>5\times10^6$ M$_\odot$, but just 1 with M$\sim10^7$ M$_\odot$. If one were to observe the Local Group from a distance, these would be distributed over an area of some 1.5$\times$1 Mpc.

Since 1999 much data has appeared, with detection limits that should have been sufficient to find clouds with masses of 10^6 M$_\odot$. But no free-floating starless clouds have been found. For instance, Pisano et al. (2004) mapped part of two nearby galaxy groups with the VLA and the DRAO telescope with $\sim$1 arcmin ($\sim$10 kpc) resolution. The groups (GH 144 and GH 158, at 33 and 45 Mpc distance, with group radii of $\sim$1.5 Mpc) were found in the catalogue of Geller & Huchra (1983). They are fairly similar to the Local Group. GH 144 has two large spirals and one large elliptical, while there are 4 large spirals and 1 large elliptical in GH 158. Toward the centers of the pointings, the VLA data had a detection limit of 1–1.5$\times10^6$ M$_\odot$, or $\sim10^{18}$ cm^{-2}. At the group's distances the VLA primary beam corresponds to $\sim$400 kpc. The DRAO data were a factor $\sim$20 less sensitive, but covered a 5 times larger area. For both groups, the VLA fields were centered on a UV-bright AGN, and pass about 450 kpc from the nearest group galaxy. Since these pointings cover $\sim$5–10% of the group's area, the de Heij et al. (2002c) model predicts that on the order of 5–10 H I clouds should have been easily detectable. Two H I objects were detected in GH 144. However, inspection of the Digital Sky Survey shows the presence of a faint dwarf galaxy near both of these (see Fig. 1).

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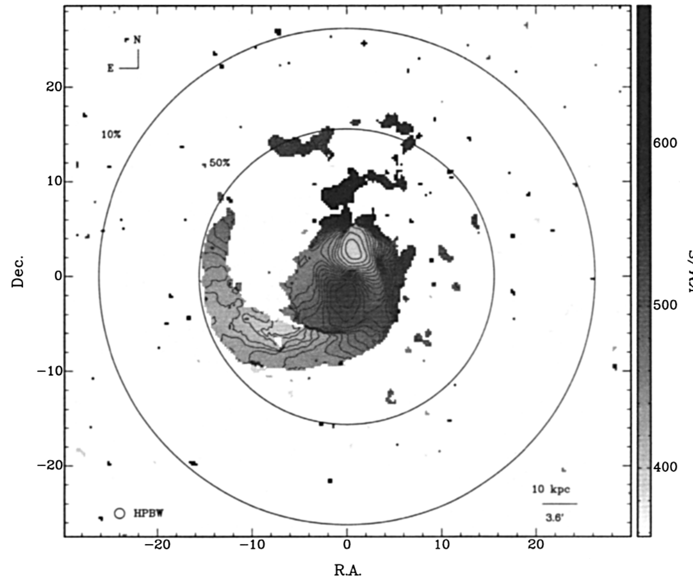

Figure 2. H I velocity field of the M 51/NGC 5195 system, showing the many HVCs surrounding this galaxy (from E. Miller, U. Mich. thesis).

Another deep survey of Local Group analogues was done by Zwaan (2001). He did a total of 300 Arecibo pointings on 5 galaxy groups similar to the Local Group, with a detection limit of 7×10^6 $M_\odot$. All detections could be attributed to optical galaxies. From a statistical analysis, he concluded that if f=0.1 there is room for at most ~10 clouds with M(H I)>3×10^7 $M_\odot$. However, if f=0.02 there could be 500 or more HVCs in the Local Group. A value of f=0.02 can be achieved if the HVCs consist of 20% H I and 80% H^+, but it also implies that virially stable HVCs must be closer than 200 kpc on average.

A slightly different approach was taken by Miller et al. (2003), who made deep (detection limit ~5×10^5 $M_\odot$) H I maps of a ~100×100 kpc region around M 51 and M 83. M 51 has undergone a tidal interaction with NGC 5195 and lots of debris clouds are found around it (see Fig. 2). M 83 on the other hand is isolated and no HVCs are found away from the main disk, although there is gas with anomalous velocities up to 100 km s^{-1} projected on the disk of M 83.

In summary, although the low metallicities found for several HVCs are consistent with the Local Group hypothesis, the other tests proposed by Blitz et al. (1999) seem to fail. HVCs *are* usually detected in Hα. 10^7 $M_\odot$ analogues are *not* found in other galaxy groups. Theoretical considerations about their state of ionization show that to get the observed H I column densities, the ensemble of distant and massive HVCs would be more massive than the Milky Way and M 31 combined. On the other hand, the limits set from Hα and from observing other galaxy groups still allow for a population of clouds within ~200 kpc from the Milky Way. The comparison with the M 51/M 83 H I maps suggests that if such a population exists, it might be related to tidal effects.

4. Highly ionized HVCs

A new angle on the possible relationship between HVCs and the Local Group has been provided by O VI absorption line data obtained using the Far Ultraviolet Spectroscopic Explorer (FUSE). This satellite was launched on 24 June 1999, and takes spectra between 912 and 1187 Å, with a velocity resolution of $\sim$20 $km\,s^{-1}$ (Moos et al. 2000; Sahnow et al. 2000). This wavelength range includes the lines of O^{+5} at 1031.926 and 1031.617 Å. O^{+5} is a good tracer of gas with temperatures of a few 10^5 K, as it is difficult to create by photo-ionization. A survey of the O VI absorption toward 100 UV-bright extragalactic targets was completed in 2003 (Wakker et al. 2003; Savage et al. 2003, Sembach et al. 2003). In 59 of the sightlines a total of 84 high-velocity O VI components were detected, with velocities $|v_{\rm LSR}|$ between 100 and 450 $km\,s^{-1}$. In the 18 months since the survey cut-off date this sample has grown to 117 high-velocity O VI components in 83 out of 138 sightlines. Figure 3 shows several examples of O VI spectra containing high-velocity O VI components.

Sembach et al. (2003) distinguished several different kinds of high-velocity O VI. Based on their velocities, six high-velocity O VI components can be identified as absorption in four nearby galaxies (M 31, M 32, M 33, M 101). Another three seem to be associated with extended halos of slightly more distant galaxies. Many are in or near directions where high-velocity H I is also found at the same velocity, particularly toward complexes A, C, WD, the Outer Arm and the Magellanic Stream. A detailed analysis of the available O VI, N V and C IV absorption for the complex C sightlines by Fox et al. (2004) suggests that the most likely explanation for the presence of hot gas associated with complex C is that this HVC is embedded in a $T{>}10^6$ K hot gaseous corona. A similar origin seems likely for the other associations between H I HVCs and O VI HVCs, although a detailed analysis of the physical conditions in these high-velocity O VI components is still lacking. Since the Magellanic Stream is about 50 kpc distant, the extent of the $T{>}10^6$ K corona must be at least 60 kpc.

Of the remaining sightlines with high-velocity O VI, four pass over the Galactic Center. Possibly this indicates the presence of an outflow, but much more study is needed. For nine high-velocity O VI components no obvious association with H I HVCs or galaxies can be found.

Of the remaining 48 high-velocity O VI features, 24 occur at high negative velocity, all at $b{<}0°$, with l between 15° and 140°. Another 24 occur at high positive velocity, all at $b{>}0°$, with l between 170° and 310°. There are several possible explanations for these absorption components.

A) Since about 2/3 of the high-positive velocity O VI components show up as an extended wing on the lower-velocity Milky Way absorption, it is possible that these absorptions originate in outflowing hot gas, associated with a Galactic Fountain flow. This does not explain the high-negative velocities seen in the southern sky, however.

B) The velocity pattern of these components also reflects that of the Magellanic Stream. However, in the southern sky the H I velocities (as well as the predicted velocities for Stream gas) are much more negative than the velocities of these O VI absorptions. In fact, in many southern directions two high-velocity O VI components are seen, one of which has velocities similar to those expected

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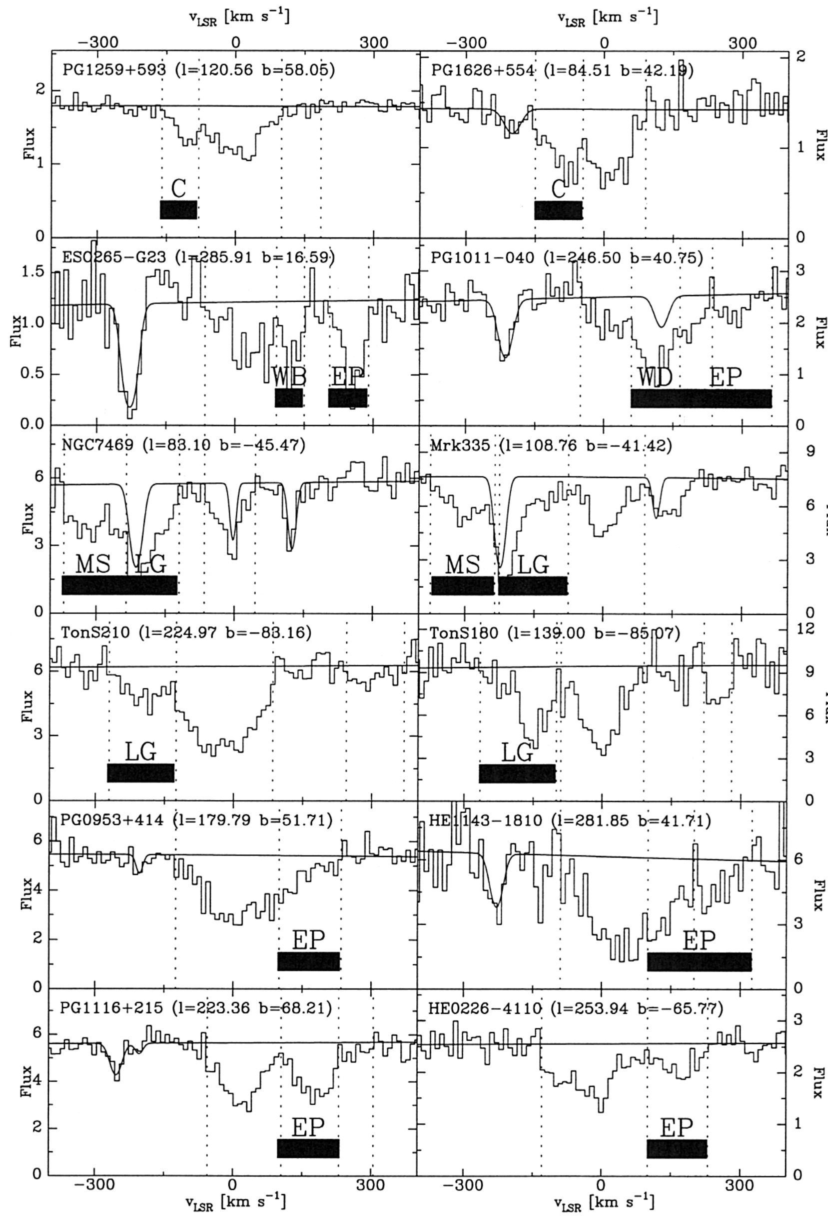

Figure 3. Examples of high-velocity O VI seen in FUSE spectra. The dotted vertical lines indicate the identified components. The thick black bars identify the high-velocity O VI: "C/WB/WD"= complex C/WB/WD. "MS"= Magellanic Stream, "LG"= possible Local Group gas, "EP"= extreme-positive velocity HVC.

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and observed for the Stream. In the northern sky this separation is not as clear. The high-positive velocity H I in the Leading Arm of the Magellanic Stream extends to b~30°, where only three sightlines are known. However, many (though not all) of the high-positive velocity O VI lies along the expected orbit of Stream gas.

C) It is notable that most Local Group galaxies in the southern sky have negative velocities, while in the northern sky most Local Group galaxies are observed at positive velocities. Therefore, the high-velocity O VI may originate in a hot gaseous filament extending between the Milky Way and M 31, through which the Milky Way is moving. Such an explanation fits very well with current hydrodynamical simulations of the universe (Cen & Ostriker 1999, Davé et al. 2001).

It remains unclear which of these three explanations is correct. More analysis is necessary.

5. Hot Local Group gas?

Observations relevant to this question are provided by the detection of O VII and O VIII absorption at X-ray wavelengths toward three targets (Nicastro et al. 2002, Fang et al. 2003, Rasmussen et al. 2003). Nicastro et al. (2003) claim that the high-velocity O VI absorptions have Local-Group like kinematics, as well as that the O VI, O VII, and O VIII absorption occur in the same 10^{6-7} K hot gas. According to them the O VII, and O VIII must originate in very tenuous gas, implying a Mpc size scale. We now consider these claims in more detail.

We have done a more thorough analysis of the kinematics of HVCs (Wakker et al., in preparation), and show that the HVC kinematics indicate that they form a non-rotating population. Beyond that, it is not possible to determine with confidence whether they are concentrated within 200 kpc from the Milky Way or whether they are more distant. Blitz et al. (1999) and de Heij et al. (2002c) compare the average velocity and the velocity dispersion of the HVC sample to that of models. Nicastro et al. (2003) calculate an average velocity vector by decomposing the observed radial velocities into three spatial components and then averaging those. We show that the derived velocities (especially the average velocity of the cloud ensemble) strongly depend on the selection criteria used to define the HVC sample, making any detailed comparison between data and model relatively unreliable.

O VII and O VIII have been detected toward several objects with Chandra (resolution 660 $\mathrm{km\,s^{-1}}$) and XMM (resolution 300 $\mathrm{km\,s^{-1}}$). In all cases the lines are not resolved, and a b-value must be assumed to derive columm densities. If collisional ionization equilibrium is assumed, then the ratio N(O VII)/N(O VI)= 250–450 for T in the range 10^{6-7} K, while N(O VIII)/N(O VI) is a much more sensitive temperature indicator.

Fang et al. (2003) measure N(O VII)=$1.8^{+0.2}_{-0.7}\times10^{16}$ $\mathrm{cm^{-2}}$ in the direction of 3C 273, using Chandra. They assume that b>100 $\mathrm{km\,s^{-1}}$, which is about the extent of the O VI high-velocity wing. They further argue that b must be large because other O VII transitions are not detected. Rasmussen et al. (2003) derive N(O VII)>0.8×10^{16} $\mathrm{cm^{-2}}$, using XMM. The O VI HVC in this direction has N(O VI)=3.9×10^{13} $\mathrm{cm^{-2}}$, implying O VII/O VI~200–450. If both originate in the same gas, this ratio implies T=10^{6-7} K. For a pathlength L=1 Mpc, N(O VII) implies a density $n = \frac{N}{LA(\mathrm{O})f(OVII)}$. For log A(O)=−4.24 (0.1 solar) and T=10^{6-7} K this gives the rather high value of $n\sim10^{-3}$–1 cm^{-3}, showing that the O VI and O VII probably do not originate in a homogeneous Local Group medium that is in collisional ionization equilibrium.

Nicastro et al. (2002) observed PKS 2155−304 with Chandra and derive N(O VII)=$4^{+2.6}_{-2.1}\times10^{15}$ cm^{-2} and N(O VIII)=$5.2^{+4.3}_{-3.9}\times10^{15}$ cm^{-2}. From XMM Rasmussen et al. (2003) find N(O VII)>4.5×10^{15} cm^{-2} toward PKS 2155−304. This assumes b=200 km s^{-1}, which is the total width of the O VI absorption in this direction. However, if the O VII is only associated with the high-velocity O VI, $b\sim$100 km s^{-1}, and the implied N(O VII) is a factor 2 higher. Since N(O VI, HVC)=1.1×10^{14} cm^{-2}, O VII/O VI=35–70 and OVIII/O VI=50–100. As Nicastro et al. (2002) note, these ratios imply that the O VI, O VII and O VIII cannot originate in a single absorber at constant temperature. They then go on to make photo-ionization models and conclude that these can explain the ionic ratios if the gas is tenuous, and thus has a large pathlength. However, the implied parameters are inconsistent with those derived for the same HVC based on the measured C IV and C III column densities (Sembach et al. 1999). Clearly more analysis is needed, and the location of this absorber remains uncertain.

Finally, with XMM Rasmussen et al. (2003) detect O VII and O VIII toward Mrk 421, with N(O VII)>4.8×10^{15} cm^{-2}. The O VI HVC in this direction has N(O VI)=2.3×10^{13} cm^{-2}, giving a ratio of ∼200, compatible with T=10^6 K.

Clearly, it is possible that some of the high-velocity O VI originates in the same hot gas that also produces O VII and O VIII absorption. However, the evidence for this remains circumstantial and a more complete analysis that includes the other ions (N V, C IV, C III, S II, etc.) is required. Also, the assumption of collisional ionization equilibrium is easily violated. Pure photo-ionization models may or may not be more appropriate. What is clearly needed are resolved O VII and O VIII profiles.

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