CONSTRAINTS ON INTERGALACTIC HYDROGEN CLOUDS

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Abstract

Searches for star-less intergalactic clouds with neutral hydrogen content roughly comparable to that of dwarf irregular galaxies are reviewed. These include searches for 21 cm emission via several strategies and for Lyα absorption along the lines of sight to QSOs, using *Hubble Space Telescope.* Clouds with H I mass $\sim 10^8$ solar masses detected in 21 cm emission number (conservatively) less than 10% of the number of dwarf irregular galaxies of similar H I mass, but low column density Lyα absorbers abound at low redshift.

1 Introduction

My task is to review searches for intergalactic clouds with neutral hydrogen content roughly comparable to that of dwarf irregular galaxies — in particular, clouds still waiting to produce stars for the first time. As previous contributions to this volume indicate, we expect H I mass in the range $10^6 - 10^8$ $M_\odot$ for the majority of dwarf irregular galaxies.

There are, in general, two ways of searching for such clouds of hydrogen: (1) by means of H I emission at 21 cm, using radio telescopes — I will mention several different approaches; and (2) by means of low redshift Lyman-α absorption in QSO spectra via *Hubble Space Telescope.*

2 21 cm emission searches

2.1 Extragalactic 21 cm emission in galaxy groups

Let me start by discussing several circumstances under which intergalactic 21 cm emission is detected — in galaxy groups for example. This is work conducted by many researchers over the past 20 years, so I will only mention a couple of typical results.

Tidal features are commonly found; some cases are more clearly of tidal origin than others. For example, the Very Large Array (VLA) map of the NGC 7463/4/5 group (Hoffman et al. 1998b) shows H I tails on NGC 7463 and UGC 12313, and a pronounced H I arc from NGC 7465 back toward NGC 7463. [Similar results for the same group have been presented by van Driel et al. (1992) and by Li & Seaquist (1994).] We also have CCD frames in B and I (B band frame is displayed in Figure 1), which show a pronounced stellar arc coincident with the H I arc connecting NGC 7465 to NGC 7464.

Occasional detached 10^8 $M_\odot$ clouds are also found, as in the VLA map (see Fig. 2) of the pair NGC 7731/2 which shows two detached clouds, each with H I mass about 3×10^8 $M_\odot$ (Hoffman et al. 1998b). In some of these cases, deep CCD images show recent star formation in the tidal tails (see the contribution by Duc later in this volume).

2.2 Serendipitous detections

There also have been a number of serendipitous detections of intergalactic clouds, when reference beams in H I redshift surveys catch H I emission in a patch of sky that was thought to be several beamwidths from any galaxy at that redshift. The Leo ring (Schneider 1985; Schneider et al. 1989) is one famous example; a large quantity of H I surrounds the bright members of the Leo group. There is little or no stellar component anywhere within the ring, and it is not clear that the H I came from any particular galaxy — as far as I know the best bet remains that the gas is primordial (Schneider 1989).

The cloud H I 1225+01 (Giovanelli & Haynes 1989) near the Virgo Cluster is another serendipitous detection. In this case there is a small patch of starlight coincident with the highest column density in NE clump. Giovanelli et al. (1995) have a more distant example, H I 2334+26 near the cluster Abell 2634.

Another example comes from my own work — the NGC 4532/DDO 137 system, in which a large diffuse H I cloud surrounds the pair of galaxies (Hoffman et al. 1993). VLA mapping (C + D array, shown in Fig. 3) (Hoffman et al. 1998a) reveals three 10^8 $M_\odot$ concentrations within the diffuse cloud, each apparent as in Arecibo spectra as well. On B and R CCD frames (Lu et al. 1998) there is no starlight visible (to 26 mag arcsec^{-2} in R). The velocity fields not well ordered; if bound, virial theorem requires substantial dark matter in each — the H I mass alone is not sufficient to bind any of the three.

We suspect that the diffuse cloud and the three concentrations are *not* due to tidal interaction between NGC 4532 and DDO 137 for the following reasons: (1) At least 1/3 of the total H I mass lies outside the two galaxies even if all the long plume stretching W and S of DDO 137 is assigned to that galaxy. (2) All the diffuse gas, including the long plume and the three concentrations, is found at lower velocity than either of the two galaxies, which is not what one expects from tides between two galaxies. (3) Much dark matter is required if the system as a whole is bound. So it seems to us that the more likely progenitor of this system was one H I-rich irregular galaxy (NGC 4532) and one large H I cloud like H I 1225+01, each with a substantial dark matter halo; diffuse gas is now reacting to surviving concentrations of dark matter within the merged halos, and perhaps even DDO 137 is a result of relatively recent star formation in one of those concentrations. A star formation history analysis of our CCD frames (UBVRI and Hα) is underway (Lu et al. 1998).

None of the serendipitous detections is a bona fide candidate for a proto-dwarf-galaxy; all have $M_H > 10^9$ $M_\odot$, comparable to that of a large spiral galaxy.

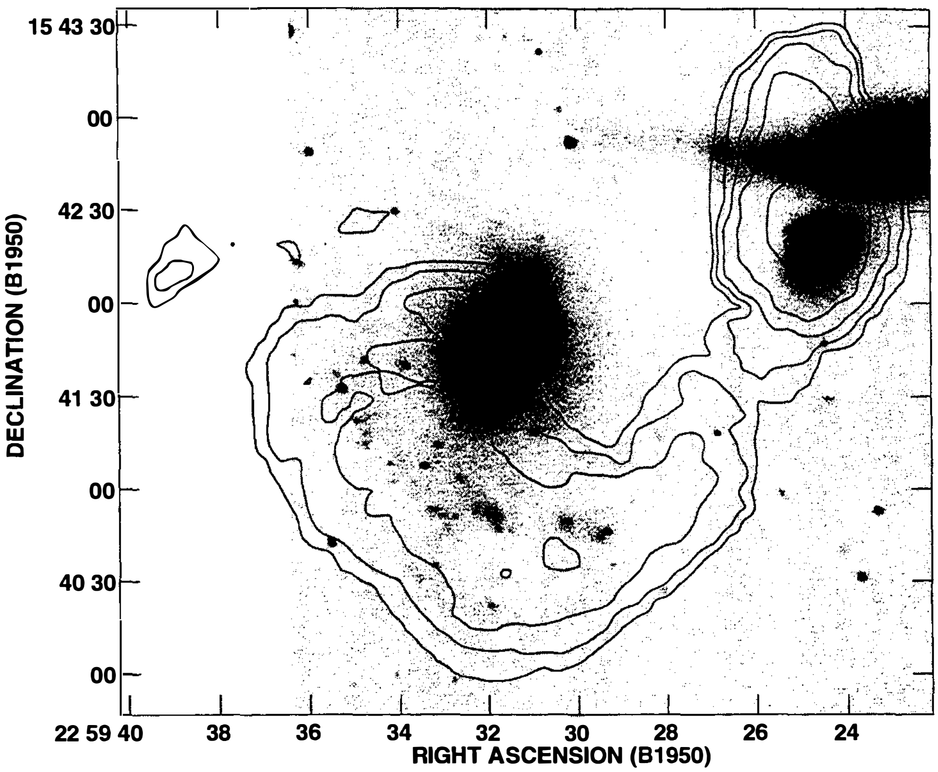

Figure 1: Contours of integrated H I emission for NGC 7464 and NGC 7465 superimposed on a B band CCD frame on the pair. All the H I in NGC 7463, visible to the NE in the CCD frame, has velocity outside the range of integration. NGC 7465 is at the center of the frame; NGC 7464 is at the E edge, just S of NGC 7463. H I contour levels are 2.2, 3.3, 4.9, 7.3 and 11.0×10^{20} atoms cm^{-2}.

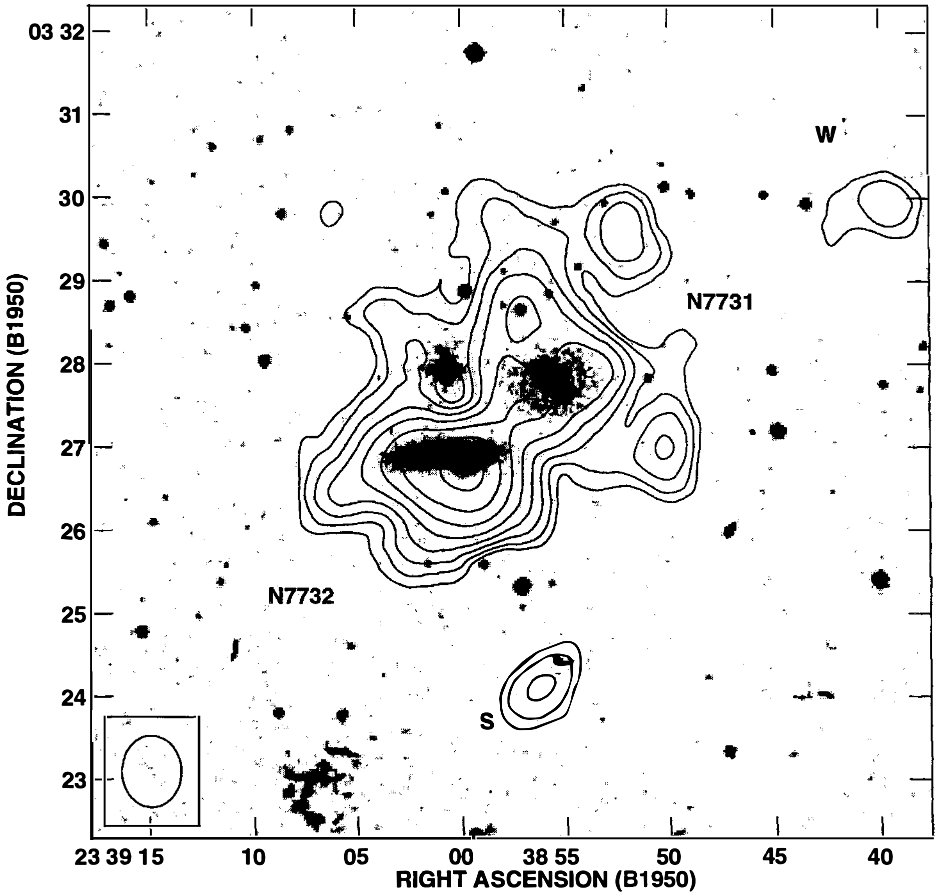

Figure 2: Contours of integrated H I emission for the pair NGC 7731 / 7732 superimposed on a Digitized Sky Survey image of the pair. H I contour levels are 1.1, 1.7, 2.5, 3.8, 5.7, 8.5, 12.7, and 19.1 $\times$ 10^{20} atoms cm^{-2}. Two detached H I clouds, labeled S and W, are indicated.

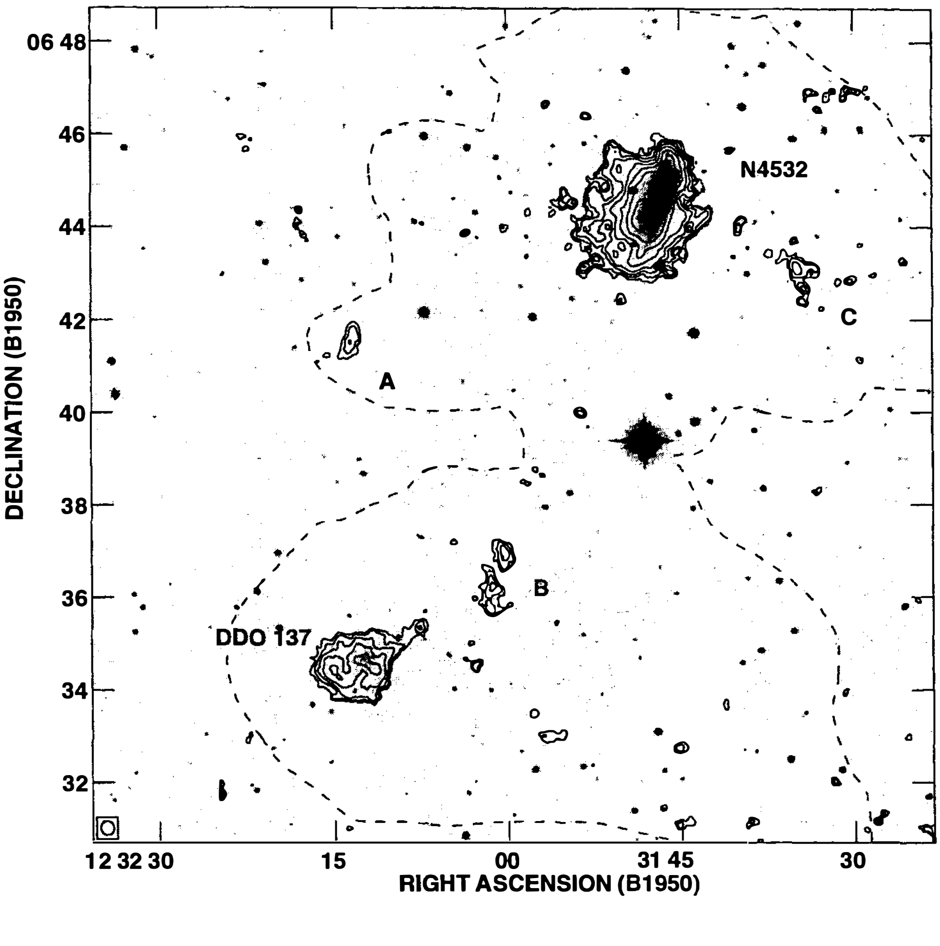

Figure 3: Contours of integrated H I emission for the NGC 4532 / DDO 137 system superimposed on a Digitized Sky Survey image of the pair. H I contour levels from the VLA mapping (solid lines) are 2.5, 3.8, 5.6, 8.5, 12.7, 19.1, 28.6, 42.9 and 64.3×10^{20} atoms cm^{-2}. The dashed curve shows the outermost contour level from the Arecibo map, at 2.0×10^{19} atoms cm^{-2}. Three distinct clouds are indicated. The Arecibo map also shows an extended plume running from DDO 137 to the E and then SE, incorporating Cloud B. All three clouds, however, can be seen as distinct features in the Arecibo spectra.

2.3 Limits from OFF-scan searches

Does that imply that our OFF-scan reference beams are only capable of picking up large, diffuse objects? Not at all. H I observers are very good at catching untargetted dwarf-sized catalogued galaxies in our ON and OFF beams — routine observation consists of OFF scan subtracted from ON, so negative signal in spectrum is most likely due to emission in the OFF beam. H I observers, especially those of us who target dwarf galaxies, now routinely inspect our spectra for OFF-scan detections and for untargetted sources in ON beams; we should easily detect any 10^8 $M_\odot$ gas cloud that falls within a couple arcmin of an Arecibo ON or OFF beam center out to well beyond Virgo cluster redshifts, and 10^6 $M_\odot$ clouds out to a few Mpc. In the VCC survey (Hoffman et al. 1989, 1996 and references therein), at least, we did not dismiss narrow signals as interference; we followed up any blip that might be an H I signal from a dwarf galaxy. There were many false alarms, but each time we checked the catalogues we found a catalogued dwarf galaxy at the OFF beam position. Arecibo is quite capable of serendipitous detection of $10^6 - 10^8$ $M_\odot$ gas clouds, but no such optically invisible cloud has been detected serendipitously to date as far as I know. The only serendipitous intergalactic signals I know about are those four large clouds mentioned earlier — not dwarf-sized clouds.

The surveyed beam area adds up — in our H I survey (Hoffman et al. 1989) of the spiral and irregular entries in the Virgo Cluster Catalog (Binggeli et al. 1985), we surveyed some 3% of the total area spanned by the Catalog, for redshifts from 0 to 4000 km s^{-1}, a total of about 1640 ON/OFF pairs. Having found none, we inferred $<$ 100 star-poor clouds with $M_H > 3 \times 10^7$ $M_\odot$ anywhere within the VCC area. That amounts to less than half as many as dwarf irregulars catalogued by BST, and far fewer than the number of dwarf ellipticals.

The most thorough analysis of the major redshift surveys, comprising several thousands of beam positions, has been carried out by Briggs (1990, 1997) and Briggs & Rao (1993). The general result is that for the VCC area, the H I mass function is consistent with a Schechter function with power law exponent 1.0 at the dwarf end to below 10^7 $M_\odot$; the field H I mass function is consistent with a Schechter function having power law exponent 1.3–1.4 with integrated H I contributing negligibly to the density parameter Ω — but still better limits are obtained from the blind surveys which I will discuss below.

2.4 H I companions

Another approach is to search in the vicinity of particular kinds of galaxies which are thought to have intense star formation as result of interaction with a nearby gas cloud. Taylor (1997 and references therein) undertook a search for H I companions of H II galaxies and of LSB galaxies as a control. H I clouds were detected within a VLA primary beam of H II galaxies statistically significantly more often than around LSB galaxies. Most of the companions have stellar components but there is one with at best a very minimal stellar component. A similar search using Arecibo was undertaken by van Zee et al. (1995).

A possibly related phenomenon is the High Velocity Cloud (HVC) system — of course, HVC are well documented around the Milky Way, and their distances and formation mechanisms are hotly debated (see review by Wakker & van Woerden 1997). There have been claims of detection of HVC complexes superposed on the disks of face-on spiral galaxies (Kamphuis & Briggs 1992; Kamphuis & Sancisi 1993; Phookun et al. 1993; Schulman et al. 1996), and we have a possible detection of an HVC complex in our Arecibo mapping of NGC 6570 (Hoffman et al. 1992). HVC are important to any discussion about intergalactic H I clouds in light of the suggestion by Blitz et al. (1998) that the velocity vectors of HVC around the Milky Way are in fact isotropic about the barycenter of the Local Group, not isotropic about the Milky Way, with the implication that HVC are much further away than the few kpc usually assumed. HVC would be distributed throughout the Local Group in the Blitz et al. model. That is a controversial suggestion to say the least, but if it is true HVC complexes have masses around 10^8 $M_\odot$ and should be found in other groups when we push sensitivities down to 10^{18} atoms cm^{-2} or less, with adequate spatial resolution.

2.5 Blind searches

The most sensitive constraints on intergalactic clouds to date have come from the blind H I searches using Arecibo while the 21cm feed motion was impaired during the upgrade construction, as discussed in the contributions by Zwaan and by Schneider to this volume. There have been, however, a number of other blind searches that should be mentioned as well.

I will omit from discussion some early searches that were sensitive only to $M_H > 10^{10}$ $M_\odot$. Several studies were sensitive to $M_H > 10^8$ $M_\odot$, as enumerated in Table 1; these found a few uncatalogued dwarf galaxies, all with stellar components visible on CCD frames (or in the Zone of Avoidance where there is too much obscuration to say).

Table 1. Blind searches, $M_H > 10^8$ $M_\odot$

Authors	Telescope	Region searched
Shostak (1977)	NRAO 300′	wide area, low z
Materne et al. (1979)	Dwingeloo & Effelsberg	nearby groups
Weinberg et al. (1991)	VLA	Perseus-Pisces
Henning (1992)	NRAO 300′	Zone of Avoidance
Barnes et al. (1997)	Parkes	Centaurus and Fornax

Several more studies have set meaningful limits on $M_H >$ few $\times 10^6$ $M_\odot$ as listed in Table 2. The earlier several of these also found uncatalogued dwarf galaxies, but no star-poor clouds. The last two entries are by far the most important; details were given in the previous contributions by Zwaan and Schneider. These were surveys conducted at Arecibo during upgrade construction, and had much greater sky coverage than previous surveys. Both spanned a redshift range $\sim 0 - 8000$ km s^{-1}. The results are summarized in the next section.

Table 2. Blind searches, $M_H >$ few $\times 10^6$ $M_\odot$

Authors	Telescope	Region searched
Lo & Sargent (1979)	OVRO	nearby groups
Schneider (1989); Schneider et al. (1989)	Arecibo	Leo ring
Hoffman et al. (1992)	Arecibo	Supergalactic Pole
Sorar (1994); Zwaan et al. (1997)	Arecibo	Arecibo H I Strip Survey
Spitzak (1996); Schneider (1997)	Arecibo	Arecibo Slice Survey

2.6 Summary of emission studies

The principle results of the surveys mentioned in the previous section (and all H I emission studies to date) as I see them are as follows: A few large clouds (not dwarfs) with very little star formation have been detected serendipitously or by blind search. One star-poor H I companion near an H II galaxy has been found, but most H II galaxies that have H I-rich companions have companions with a significant number of stars. A couple of isolated $10^7 - 10^8$ $M_\odot$ star-poor clouds have been detected by blind search, but those amount to < 10% of all H I clouds with mass < 10^8 $M_\odot$ — most have either a LSB stellar component or active star formation. The field H I mass function rises moderately steeply, $\alpha \sim 1.4$, to < 10^7 $M_\odot$. The contribution to the density parameter in the form of H I is on the order of 2×10^{-4} h^{-1}, dominated by L_* spiral galaxies and including the extrapolation to masses below 10^7 $M_\odot$. The mass function would have to rise much more steeply ($\alpha > 1.7$) below 10^7 $M_\odot$ for low mass H I clouds to make significant contribution to Ω; none of the studies to date have been sensitive enough to say much about such low masses (but the surveys in progress, Table 3, may eventually reach that sensitivity).

Table 3. Blind searches in progress

Authors	Telescope	Region searched
Henning (1997)	Dwingeloo	Dwingeloo Obscured Galaxy Survey
Kilborn (1998)	Parkes	Parkes Multi-Beam Survey
Schneider (1998)	Arecibo	Arecibo Dual-Feed Survey
van Driel (1998)	Nançay	Northern hemisphere

3 Lyα absorption searches

H I emission studies to date are limited to column densities for gas that fills the beam around 10^{18} cm^{-2} at best; it is not clear that there is much point in searching to much lower column density since clouds with < 10^{18} atoms cm^{-2} should be ionized by extragalactic UV (Corbelli & Salpeter 1993; Maloney 1993; Dove & Shull 1994). But 21cm emission is not the only way to detect H I; *HST* can see H I in absorption to much lower neutral column density. Absorption lines with column densities < 10^{17} cm^{-2} are dubbed the Lyα forest; *HST* sees around 15 such Lyα lines per unit redshift down to redshift 0 (Bahcall et al. 1993). Forest lines are occasionally found in voids, several Mpc from the the nearest galaxy visible in CCD frames (Shull et al. 1996); but there is a definite correlation with galaxies for the bulk of the absorber sample — in particular, the area filling factor in groups is ~ 1 (Le Brun & Bergeron 1998).

The origin of the forest absorbers remains unclear (Le Brun et al. 1996): Tidal debris is a popular explanation (Morris & van den Bergh 1994; Mo & Morris 1994) for the absorbers in groups (but doesn't work for void absorbers). Far-reaching ($\sim$ Mpc) power-law galactic halos (Maloney 1992) are invoked for the stronger lines (Lanzetta et al. 1995; Chen et al. 1998), but certainly cannot explain all observations. The lowest redshift 3C 273 absorber is a case in point; there are two galaxies nearby at similar redshift — one is the Giovanelli-Haynes cloud, H I 1225+01; the other is a more ordinary dwarf irregular, MCG +00-32-16. The rotation velocity of H I 1225+01 is nowhere near enough to reach the absorber (the difference being 272 km s^{-1}); MCG +00-32-16 is closer in redshift but the sense of rotation is wrong (Hoffman et al. 1998c). So primordial gas clouds, still accreting onto larger galaxies, remain a viable explanation for a significant number of the forest absorbers.

Lyman Limit Systems (LLS; $\sim 10^{17}$ cm^{-2}) are far more rare (about 1 in 30 by comparison to forest lines — Storrie-Lombardi et al. 1994; Stengler-Larrea et al. 1995), but could be detectable in H I emission with effort. There have been too few low-redshift LLS detected for detailed correlation studies, and several options remain open for the origin of the LLS: LLS could be the same as the forest, just the high column density tail of a distribution; extended galactic disks are perhaps a viable explanation for a larger fraction of the LLS than of the forest. LLS could be systems like H I 1225+01 or NGC 4532/DDO 137 — a QSO seen through outskirts of either system would produce a LLS. Or LLS could be HVC complexes in the picture of Blitz et al. (1998).

Let me end with a question to motivate further research: Are the proto-dwarf clouds mainly ionized? Can we come up with a scenario whereby they compress and cool and become neutral only after collisions or mergers in a group environment?

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