Cold Gas in High Redshift Galaxies

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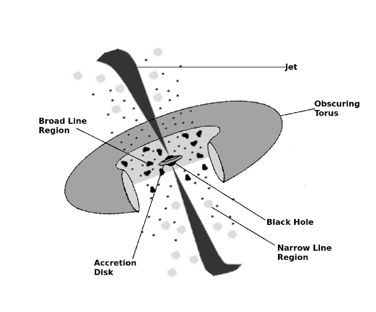
Motivation

- Tracing cool neutral hydrogen gas, reservoir of star formation.
- HI 21 cm line in absorption can be used to detect neutral hydrogen gas at high redshifts.
- AGNs act as background radio 'torch'.



- Both, distributional and kinematical properties of the gas can be studied.
- HI 21 cm absorption can be used to detect inflows and outflows relative to the AGN.
- Physics of the AGN can be studied, the surrounding gas may be the source of the fuel for AGN activity.
- Conversely, AGN can regulate star formation, and growth of the host galaxy, through mechanical feedback (through outflows).

Previous H I 21 cm studies

- More than hundred searches, with $\gtrsim 60$ detections, mostly at $z < 1$ (eg. Vermeulen et al., 2003, Gupta et al., 2006, Gereb et al., 2015).
- Detection rate:
  $\gtrsim 30\%$ at $z < 1$.
  $16^{+13}_{-8}\%$ at $z > 1$, (just 4 detections, with 25 searches).
- Possible redshift evolution.
- However, the uncertainty is large.
- Moreover, most studies at all redshifts have targetted highly heterogeneous samples. Difficult to interpret the results.
- High UV and/or radio luminosities of high-z AGNs, possible reason for the lower detection rate (Curran & Whiting, 2010).
- However, their sample was also highly heterogeneous.

Sample selection

- We targetted a large, uniformly-selected sample. A large fraction of sources at $z > 1$.
- To probe dependence of the strength of associated H I 21 cm absorption, on redshift, UV and radio luminosity, etc.
- Primary criterion: Radio source compactness. Intervening gas has a covering factor ≈ 1.
- Flat-spectrum and Gigahertz peaked spectrum sources : two classes of compact AGNs.
- Radio spectra are either inverted or flat at low radio frequencies, due to synchrotron self-absorption in compact and optically thick medium.

Flat-spectrum and GPS sources

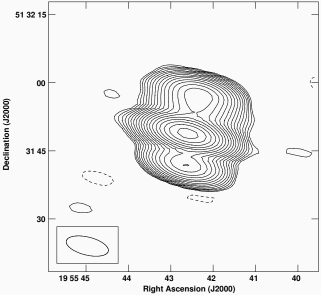
- Flat-spectrum sources: Primary targets, with $\alpha > -0.5 (S_\nu \propto \nu^\alpha)$ between 1.4 and 4.8 GHz.
- Caltech Jodrell Bank Flat-spectrum (CJF) sample (Taylor et al., 1996). (Nearly complete sample)
- Total 74 sources, 21 at $z < 0.4$, 46 at $1.1 < z < 1.5$ and 7 at $3.0 < z < 3.6$.
- 29 sources, mostly at $z < 1$, have searches available in literature.

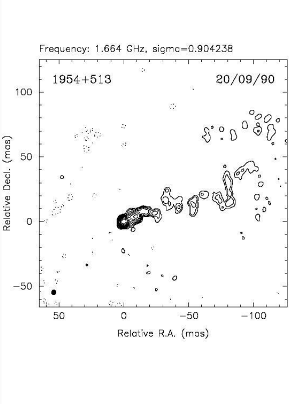
- GPS sources: Total of 58, with inversion frequency lying between 300 MHz and 5 GHz (e.g. Labiano et al. 2007).
- 23 sources of the sample, mostly at $z < 0.7$, already have searches for associated H I 21 cm absorption in the literature.
- We observed 12 sources, 9 at $z < 0.4$ and 3 at $1.1 < z < 1.5$.

Observations and results

- The GMRT's legacy 1420 MHz, 610 MHz and 327 MHz receivers were used, respectively, for the sources at $z < 0.4$, $1.1 < z < 1.5$ and $3.0 < z < 3.6$.
- Typical velocity resolution and coverage: $10 - 30$ km/s and $4000 - 16000$ km/s, depending on observing band and correlator
- Total observing time : ≈ 200 hrs, with 75 hrs in 1420 MHz band, 90 hrs in 610 MHz band and 45 hrs in 327 MHz band.
- We obtained clean spectra for 63 CJF sources (4 detections and 59 non-detections), and 7 GPS sources (2 detections and 5 non-detections).
- Non-detections were smoothed to ≈ 100 km/s, to be consistent with the literature sample, and to compare the optical depths.

New Detection: TXS 1954+513, at $z = 1.223$

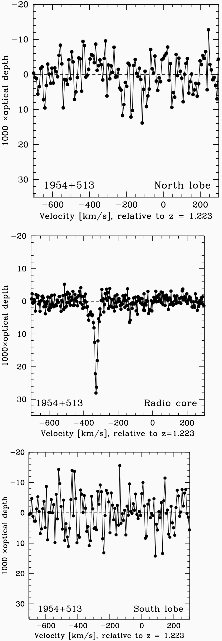




Xu et al. (1995)

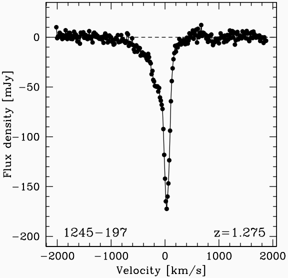
- Classified as a blazar, based on optical, X-ray and radio characteristics in literature.
- Misalignment could be due to twisted radio jet, due to interaction with the ambient medium,
- Or, due to jet precession. (e.g. Conway & Murphy 1993; Appl et al. 1996).

TXS 1954+513, at $z = 1.223$



- Fifth known absorber at $z > 1$. (Aditya et al., 2017)
- $N_{HI} = (1.305 \pm 0.067) \times 10^{20} \times (T_s/100K)$ per cm^2
- $L_{UV} \approx (4.1 \pm 1.2) \times 10^{23}$ W Hz^{-1}, using Lick observatory measurements at B and R bands.
- Absorption is blueshifted from the AGN redshift of $z = 1.2230 \pm 0.0001$ (Lawrence et al., 1996) by ≈ 328 km s^{-1}.
- Probably, the gas is being driven out by the VLBI scale radio jet.

New Detections at $z > 1$



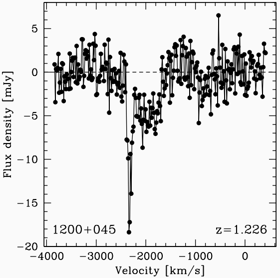
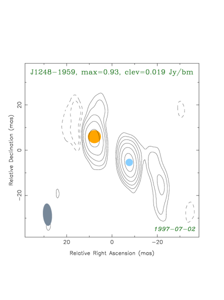
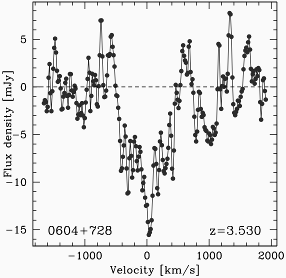
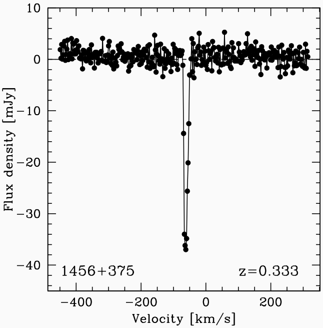


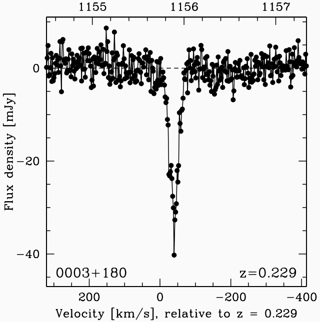
Image: Sokolovsky et al., 2011





New detections at $z < 0.4$





- Both are classified as blazars in the literature (e.g. Massaro et al., 2009).
- Absorption against the core or beamed emission from the jets.
- $N_{HI} = (6.98 \pm 0.15) \times\ 10^{20}\ T_s/100\ K\ cm^{-2}$ (1456+375). $N_{HI} = (3.54 \pm 0.1) \times\ 10^{20}\ T_s/100\ K\ cm^{-2}$ (0003+380).

Redshift evolution, CJF sample

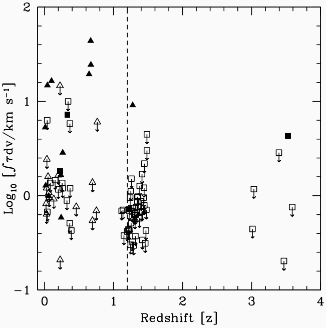
- We combined our sample of 63 sources with 29 sources (CJF sample) in literature.
- Smoothed our non-detections to 100km/s.
- Total sample size is 92. On dividing the total sample at $z_{med} = 1.2$,

Table 1: CJF sample

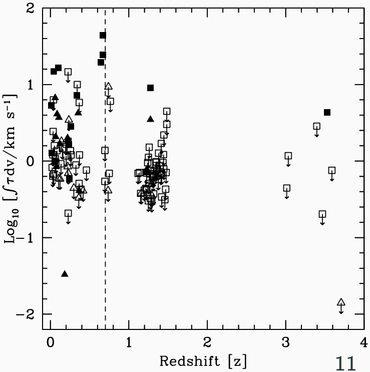
	Detections	Non-detections
$z < z_{med}$	13	33
$z > z_{med}$	3	43

- $z < z_{med}$: $28^{+10}_{-8}\%$
  $z > z_{med}$: $7^{+6}_{-4}\%$
  Consistent at 2.1σ

Redshift evolution

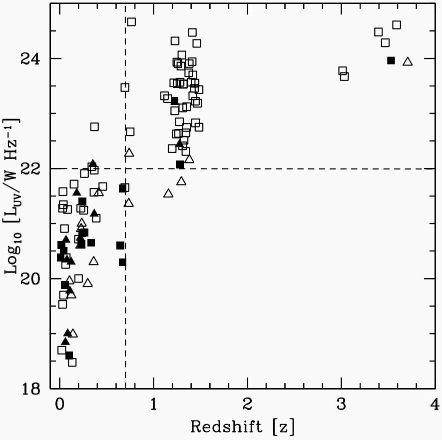


- 4.1σ significance, in the sample of 119 compact AGNs (CJF+GPS).
- Strongest evidence.



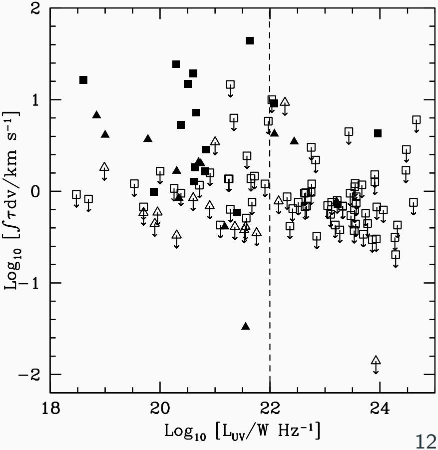
- A Peto-Prentice two-sample test: 3σ significance (CJF sample).
- **First significant evidence for a possible redshift evolution in a uniformly-selected sample.** (Aditya et al., 2016)

CJF+GPS, UV effect

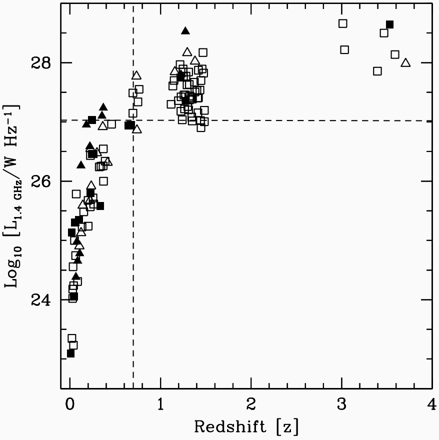


- $z_{med} = 0.7$
- Gehan-Wilcoxon test: 9.7σ significance.

- $L_{UV,\ med} = 10^{22.0}$W Hz^{-1}
- Peto-Prentice test : $\approx 3.5\sigma$ significance.

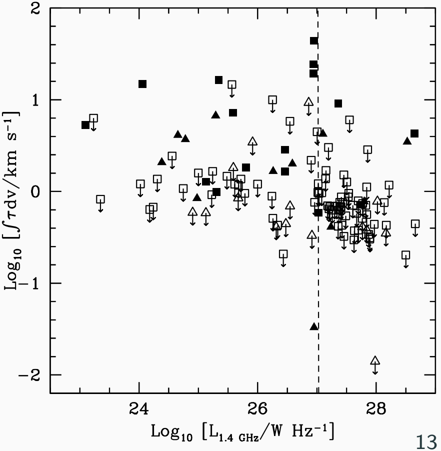


CJF+GPS, Radio luminosity effect



- $z_{med} = 0.7$
- Gehan-Wilcoxon test: 10.3σ significance.

- $L_{rad,\ med} = 10^{27.0}$W Hz^{-1}
- Peto-Prentice test : $\approx 3.5\sigma$ significance.



Summary

- We obtained 6 new detections of associated H I 21 cm absorption, with 4 at $z > 1$.
- Nearly doubled the number of detections at $z > 1$.
- Obtained first statistically significant evidence for redshift evolution of the strength of H I 21 cm absorption in AGN environments, in a uniformly-selected sample.
- We find strong dependence of the strength of H I 21 cm absorption on redshift, rest-frame 1216 Å AGN lumisoity, and rest-frame 1.4 GHz AGN luminosity.
- It is currently not possible to break the above degeneracy since most of the high-luminosity AGNs in our sample lie at high redshifts.